

MANAGEMENT STRATEGIES FOR THE LOWER BERG RIVER AQUIFER SYSTEM, WESTERN CAPE

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DECLARATION

I, Nicolette VERMAAK, hereby declare that the dissertation hereby submitted by me to the Institute for Groundwater Studies in the Faculty of Natural and Agricultural Sciences at the University of the Free State, in fulfilment of the degree of *Philosophiae Doctor*, is my own independent work. It has not previously been submitted by me to any other institution of higher education. In addition, I declare that all sources cited have been acknowledged by means of a list of references.

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Nicolette VERMAAK

28 February 2021

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ABSTRACT

The development of the town of Saldanha is a coastal town in the semi-arid west coast of South Africa was constrained by lack of reliable water resources till the Berg River pipeline that was built in the 1940s to provide water to the military installations. This supply was later turned over to the town, and the area began to grow. Saldanha Bay is one of the few natural harbours in South Africa, and the export of steel in the late 1990s resulted in the development of the Langebaan Road wellfield.

The groundwater potential of the coastal aquifer system in the area was discovered in the early 1970s when a number of artesian wells with good water quality were drilled. This led to the declaration of the Saldanha Subterranean Government Water Control Area, which was later expanded. Timmerman did further groundwater exploration in the area for the Department of Water Affairs. The work by Timmerman was very detailed, but some misconceptions about the system was built into the conceptual model, and later the model that was built. Timmerman divided the Lower Berg River aquifer system into four units – the Adamboerskraal, Langebaan Road, Elandsfontein and Grootwater aquifer units. The system consisted of a number of deeply incised palaeochannels into the bedrock that was filled with layers of different Cenozoic deposits. This work remained the foundation of the understanding of the Lower Berg River Aquifer System for many years.

After the wellfield became operational in December 1999 discrepancies between the measurements and the Timmerman conceptual model were observed. The artificial recharge test carried out by the CSIR during the winter of 2008 and 2009 raised some more questions. The need to re-evaluate the conceptual model with the additional monitoring data was identified. The improved scientific understanding would be used to develop a management strategy for the management of the groundwater resources in an area.

Analysis of the water level data and the groundwater chemistry were done. Time series graphs were plotted, and comparisons were done between data sets. The analysis of the data shows a clear link between the Adamboerskraal and the Langebaan Road aquifer unit, with the palaeochannel below the Berg River. The link between the Langebaan Road and Elandsfontein aquifer units was also established through the groundwater levels and the groundwater chemistry. This is possible through a break in the bedrock high – a palaeochannel connecting the two units – and the shale-granite contact. The link between the Elandsfontein and Grootwater aquifer unit could not be established conclusively.

A conceptual model was constructed using the data that was available. The conceptual model included a regional understanding of the Berg River catchment area, with possible recharge from the mountains in Franschhoek through the Colenso Fault System. It also provides a clearer picture of the local situation in the study area. The deposits of Cenozoic layers are not uniform, with the clay layer pinching out at the edges of the palaeochannel, which at times brings the different aquifer layers in direct hydraulic contact. The system thus consists of different layers with unique

characteristics that are interlinked. The Lower Berg River Aquifer System should thus be treated as a complex integrated aquifer system.

An action plan for the development of an adaptive management strategy framework was developed with the different components or principles that needed to be included. The site-specific adaptive conditions were taken into consideration and it is recommended that these items be included in the development of the management plan with relevant stakeholders for maximum impact.

Key words: Coastal aquifer; Lower Berg River Aquifer System; adaptive management

Table of Contents

Explanation of Terms	17
List of abbreviations	20
Chapter 1: Introduction.....	21
1.1 General Research Statement	22
1.2 Problem statement	27
1.3 Research aim and objectives.....	28
1.4 Research statement	28
1.5 Thesis structure	29
Chapter 2: Theoretical Framework	30
2.1 Coastal Aquifers.....	31
2.1.1 <i>Coastal aquifers from other parts of the world</i>	32
2.1.2 <i>Coastal aquifers in South Africa</i>	34
2.2 Groundwater management	36
2.2.1 <i>Legislative Framework</i>	37
2.2.2 <i>International best practice</i>	37
2.2.3 <i>International legislation</i>	42
2.2.4 <i>South African Legislation</i>	45
2.3 Adaptive Management as management strategy.....	64
2.3.1 <i>Examples of Adaptive Management</i>	68
2.3.2 <i>Why Adaptive Management for aquifers?</i>	75
2.4 Summary.....	78
Chapter 3: Study Area.....	79
3.1 Introduction.....	79
3.2 Location	80
3.3 Climate	81
3.3.1 <i>Temperature</i>	83
3.3.2 <i>Wind</i>	83
3.3.3 <i>Evapotranspiration</i>	84
3.3.4 <i>Humidity</i>	84
3.3.5 <i>Rainfall</i>	84
3.4 Topography.....	86
3.5 Vegetation.....	89

3.6 Land-use	90
3.7 Geology.....	91
3.7.1 Basement.....	94
3.7.2 Cenozoic Deposits.....	97
3.7.3 Palaeochannels and fault systems	110
3.8 Water Resources	129
3.8.1 Surface water	129
3.8.2 Groundwater	131
3.8.3 Other water resources	150
3.9 Historical Conceptual Model.....	151
3.10 Summary.....	162
Chapter 4: Geohydrological Characteristics	163
4.1 Rainfall.....	164
4.2 Recharge	172
4.2.1 Calculations	173
4.2.2 Types of recharge observed / mechanisms.....	174
4.2.3 Recharge areas	174
4.3 Water levels	175
4.3.1 Langebaan Road aquifer unit.....	175
4.3.2 Elandsfontein Aquifer Unit.....	189
4.3.3 Adamboerskraal Aquifer Unit.....	196
4.3.4 Grootwater Aquifer Unit	200
4.4 Yield estimations, storage potential and flow	207
4.5 Hydrochemistry	208
4.5.1 Rainfall	208
4.5.2 Surface water.....	209
4.5.3 Groundwater	210
4.6 Correlation between surface water and groundwater levels.....	225
4.7 Discharge	227
4.8 Groundwater dependent ecosystems	228
4.9 Summary.....	230
Chapter 5: Conceptual Model.....	232
5.1 Regional Picture.....	234
5.1.1 Palaeochannels.....	234

5.1.2 <i>Fault Systems</i>	236
5.2 Local situation	238
5.3 Geological Conceptual Model	256
5.4 Summary	260
Chapter 6: Model evaluation	261
6.1 Timmerman (1988)	265
6.2 Berg WAAS (2008)	266
6.3 Seyler, et al. (2016)	270
6.4 Summary	271
Chapter 7: Management Strategies	273
7.1 Adaptive Management Strategies for Coastal Aquifers	274
7.1.1 <i>Protection</i>	275
7.1.2 <i>Regulation</i>	278
7.1.3 <i>Use</i>	279
7.1.4 <i>Planning</i>	279
7.1.5 <i>Monitoring</i>	282
7.1.6 <i>Conservation</i>	284
7.1.7 <i>Operation</i>	285
7.1.8 <i>Infrastructure</i>	285
7.1.9 <i>Assessment</i>	286
7.1.10 <i>Institutional arrangement</i>	286
7.1.11 <i>Capacity and Skills</i>	288
7.1.12 <i>Awareness, information, stakeholder participation</i>	289
7.2 Management Strategy Action Plan for the Lower Berg River Aquifer System	294
7.3 Flow process	307
7.4 Summary	310
8. Discussion	311
9. Conclusion and Recommendations	317
References	319

Table of Figures

Figure 1: Berg River/Saldanha Bay pipeline in 1942/43 (Visser, et al, 2008).	23
Figure 2: Reconciliation of water supply and requirement for the Reference Scenario for the WC WSS before the drought (DWS, 2015).	26
Figure 3: Medium to long term reconciliation options to manage the water balance of the WCWSS, taking the potential impacts of climate change into consideration (DWS, 2019).	27
Figure 4: Distribution of coastal Cenozoic sediments in South Africa (Roberts, et al., 2006).	35
Figure 5: The Cenozoic deposits of South Africa (after Dept. Mineral & Energy Affairs, 1984) used for the identification of the boundaries of coastal aquifers. Their surface area is given in km ² (Campbell, et al., 1992).	35
Figure 6: Map showing the Subterranean Government Water Control Areas in the Berg River catchment area.	47
Figure 7: Satellite image showing quaternary drainage areas for the Berg River area (red polygons) and the estimated extent of the Lower Berg River Aquifer System (blue polygon) (Vermaak, et al., 2019b).	50
Figure 8: Illustration to show the difference between the conventional understanding of the reserve with the situation for groundwater (Vermaak, et al., 2019b).	51
Figure 9: Satellite image showing the quaternary drainage areas for part of the Berg Area (Vermaak, et al., 2019b).	52
Figure 10: Satellite image showing the quaternary drainage areas for the False Bay basin containing the Cape Flats Aquifer (Vermaak, et al., 2019b).	53
Figure 11: Example of protection zones around a wellfield (Halton-Hamilton, 2010).	55
Figure 12: Groundwater availability according to GRAII compared to registered water use on WARMS per water management area (Fourie, 2018; Vermaak, et al., 2019b).	58
Figure 13: Groundwater availability according to GRAII compared to registered water users on WARMS per province (Fourie, 2018; Vermaak, et al., 2019b).	59
Figure 14: Abstraction volumes and meter readings for BG00124 in the Hopefield area (Vermaak, et al., 2019b).	60
Figure 15: Results of a hydrocensus in Bellville (Vermaak, et al., 2019b).	61
Figure 16: Quaternary drainage areas for the Berg River catchment with hydrological stations (Vermaak, et al., 2019b).	62
Figure 17: Adapted from CMP Adaptive Management Cycle (2013).	66
Figure 18: Planning life cycle (DWS, 2017; Fourie, 2019).	67
Figure 19: Flow diagram of the project process (DWS, 2017; Fourie, 2017; Fourie, 2019).	68
Figure 20: General approach of water management used in Denmark (Danish Ministry of the Environment [a], undated).	69
Figure 21: Public participation in the different stages of a groundwater mapping project (Jensen, 2017).	71
Figure 22: Water quality monitoring and evaluation process (adapted from van Wyk, 2001).	74
Figure 23: Satellite image showing the study area.	81
Figure 24: Position of the Cape Coast in relation to the major pressure and wind systems of the Southern Hemisphere (Heydorn and Tinley, 1980).	82
Figure 25: Synoptic patterns over Southern Africa during summer and winter seasons in relation to the generation of airborne moisture and the general migration pathways (van Wyk, et. al., 2011).	83

Figure 26: Mean Annual Precipitation of Study Area, showing Rainfall Stations used to calibrate the original CCWR MAP dataset (Woodford, et al., 2003).....	85
Figure 27: Mean annual rainfall for the central part of the study area (Woodford and Fortuin, 2003)..	86
Figure 28: Physiography of Study Area (Woodford, et al., 2003).	88
Figure 29: The topography of the northern part of the study area (Woodford and Fortuin, 2003).	89
Figure 30: Vegetation Types of the Study Area (Woodford, et al., 2003; after Low and Rebelo, 1996). ...	90
Figure 31: Land Use of the area (DWAF, 2008).....	91
Figure 32: Geology of the Study Area (Woodford, et al., 2003).....	93
Figure 33: Simplified surface geology of the study area (Woodford and Fortuin, 2003).	94
Figure 34: Geology of the Berg River catchment area showing the fault lines and granite plutons (Roberts, et al., 2006).	96
Figure 35: Isopachs of Cenozoic strata in the Saldanha, Vredenburg and Velddrif environs. The depocentres record the locations of ancient channels of the Berg River and possibly the Groen River in the east (Roberts & Siegfried, 2014).	98
Figure 36: Stratigraphy of the Elandsfontyn Formation in borehole G30878 on the farm Elandsfontyn 349, west of Hopefield (after Rogers, 1980; Theron, 1992).	100
Figure 37: Stratigraphy and sedimentology of the fluvial Elandsfontyn Formation, shallow-marine Varswater Formation and aeolian Langebaan Formation in the S1 borehole (after Rogers; Roberts & Siegfried, 2014).	101
Figure 38: Subsurface distribution of the Elandsfontyn Formation in the Saldanha, Vredenburg and Velddrif environs. (Modified after Timmerman, 1988 and Cole and Roberts, 1996; Roberts & Siegfried, 2014).	102
Figure 39: Lateral lithofacies relationship in the Varswater Formation as exposed in the New Quarry, Varswater (adapted from Dingle <i>et al.</i> , 1983 and Hendey, 1981b; Theron, 1992).	104
Figure 40: Subsurface distribution of the Varswater Formation (Roberts, 2006b; Roberts and Siegfried, 2014).	105
Figure 41: Dune field morphology along the lower west coast (modified from Geological Survey of South Africa, 1990). The exclusive development of dune plumes, whose orientation reflects the south-southwesterly dune building wind is clearly apparent (Roberts, et al., 2009).	108
Figure 42: Palaeochannel map of the Lower Berg River Valley aquifer system, showing basement contours (Roberts and Siegfried, 2014).	111
Figure 43: Modelled surface, shown as depth to granite, prior to deposition of the Sandveld Group (Roberts, et al., 2017).	113
Figure 44: Schematic synthesis for Saldanha Bay during deposition of the Elandsfontyn Formation (Roberts, et al., 2017).	114
Figure 45: A. Schematic block-diagram through a brittle fault zone showing the development of a damage zone around the fault core. B. Cross-section through the fault (from Schröckenfuchs, et al, 2015; Kisters, 2018)	115
Figure 46: Fault zone architecture (Lin, et al., 2015).....	116
Figure 47: Weathering of the country rock and the damage zone of a fault (Cherry, 2016).	117
Figure 48: Mylonites, faults and Malmesbury hornfels (Schoch, 1972).	122
Figure 49: Geological map of the Dufnefontein Nuclear Site Area with the 8km and 4km radii that guide the geological investigation (CGS, 2007; SRK, 2018).	126
Figure 50: Monthly run-off in the Berg River (after K.M.G. Timmerman, 1985; Timmerman, 1988).	130
Figure 51: Groundwater Management Units and Mean Annual Recharge for the Study Area (Woodford, et al., 2003).	135

Figure 52: Groundwater contours for the upper unconfined layer with flow directions (Woodford and Fortuin, 2003).....	138
Figure 53: Water level elevation in the Lower Aquifer Unit of the Langebaan Road and Elandsfontein Aquifer Systems and Thickness of Cenozoic Deposits (Woodford, et al., 2003; Woodford and Fortuin, 2003).....	139
Figure 54: Zones of Groundwater Development Potential in relation to the existing Saldanha-Berg and Swartland water reticulation scheme (Woodford, et al., 2003).....	142
Figure 55: Natural discharge [L/s] from the Langebaan Road and Elandsfontein aquifer units to the rivers, wetlands, pans, springs and the sea (Woodford, 2004).....	143
Figure 56: Cone of depression associated with the Langebaan Road wellfield after a number of years in operation (Woodford and Fortuin, 2003).....	144
Figure 57: Groundwater use in the Langebaan Road and Elandsfontein aquifer units (Woodford and Fortuin, 2003).....	145
Figure 58: Groundwater Quality variability in the Study Area in terms of Electrical Conductivity (Woodford, et al., 2003).....	146
Figure 59: Electrical conductivity in mS/m as an indication of the water quality of the Langebaan Road and Elandsfontein aquifer units (Woodford 2004).....	147
Figure 60: Water quality of the upper aquifer layer of the Langebaan Road aquifer unit (Woodford and Fortuin, 2003).....	148
Figure 61: Water quality of the lower aquifer layer of the Langebaan Road aquifer unit (Woodford and Fortuin, 2003).....	148
Figure 62: Lower Berg River and Yzerfontein Subterranean Government Water Control Areas.....	150
Figure 63: Lithostratigraphical profile showing the sedimentology of the aquifer system (Timmerman, 1988).	153
Figure 64: Thickness of the Elandsfontyn Formation coarse sand and gravel, indicating the base of the Langebaan Road and Elandsfontein aquifer units (Woodford and Fortuin, 2003; after Timmerman, 1985a).....	154
Figure 65: Cross-section of the conceptual model of the aquifer system (Woodford and Fortuin, 2003; Woodford, et al., 2003).....	155
Figure 66: Map showing the study area (Timmerman, 1985b; as adapted by Woodford and Fortuin, 2003).....	156
Figure 67: Water level fluctuations G33320-VL1 versus Abstraction in the WCDM Wellfield (Woodford and Fortuin, 2003).....	157
Figure 68: Water level fluctuations in Borehole G33326 versus [A] Wellfield Abstraction and [B] Monthly Rainfall (Woodford and Fortuin, 2003).	158
Figure 69: Isopachs of the Elandsfontyn Clay Aquitard (Woodford and Fortuin, 2003).	159
Figure 70: Conceptual model of groundwater flow in the Langebaan Road and Elandsfontein aquifer units (DWAF, 2008).....	160
Figure 71: Conceptual model of the recharge area (Tredoux and Engelbrecht, 2009).	161
Figure 72: Development of conceptual models over the years.....	162
Figure 73: Satellite image showing the location of the rainfall stations (WISH; Lukas, 2012).	168
Figure 74: Time series graph of rainfall for stations in the study area.	169
Figure 75: Average rainfall for the study area through the year.....	170
Figure 76: Time series graph for rainfall station at Farm Langrietvlei from 1897 to 2000.	172
Figure 77: Satellite image showing the distribution of a selection monitoring points for the Langebaan Road aquifer unit (WISH; Lukas, 2012).	176

Figure 78: Time series graph of water levels for G33323.....	177
Figure 79: Graph showing the variation in water levels in a hydrological year for borehole G33323 on the historical background.	178
Figure 80: Groundwater level change index of 1-, 3-, 5- and 10-year intervals for G33323 with annual water levels.....	179
Figure 81: Time series graph of water levels for borehole G33327.	180
Figure 82: Time series graph showing the water levels measured in borehole G33327 compared to the abstraction at the Langebaan Road wellfield.	181
Figure 83: Graph showing the variation in water levels in a hydrological year for borehole G33327 on the historical background.	182
Figure 84: Groundwater level change index for borehole G33327 – 1-year, 3-year, 5-year and 10-year intervals.	183
Figure 85: Time series graph comparing waterlevels from the upper and lower aquifer layers at Langebaan Road wellfield.	184
Figure 86: Time series graph showing the water levels as measured in borehole G33327 compared to the rainfall measured in the DWS rain gauges in the area.....	185
Figure 87: Graph showing the correlation between water levels and rainfall for G33323 and G33323-RF.	186
Figure 88: Water levels in borehole G33323 compared to the rainfall measurements in G33323-RF, with a 6-month moving average.	187
Figure 89: Water levels in G33323 compared to the CDM of the rainfall readings of G33323-RF.....	188
Figure 90: Graph showing the water levels for boreholes G46023 and G46024 with the rainfall recorded by G46024-RF (Hydras3).	189
Figure 91: Satellite image showing the distribution of a selection of monitoring points on the Elandsfontein aquifer unit (WISH; Lukas, 2012).	190
Figure 92: Photograph showing the four piezometers of G33329 (taken on 21 January 2009).....	191
Figure 93: Time series graphs for the four piezometers of G33329.	192
Figure 94: Time series graph of water levels for G33317 with cumulative deviation from mean.	193
Figure 95: Graph showing the variation in water levels in a hydrological year for borehole G33317 on the historical background.	194
Figure 96: Groundwater level change index for borehole G33317 at 1-year, 3-year, 5-year and 10-year intervals.	195
Figure 97: Time series graph of water levels for BH1A.	196
Figure 98: Satellite image showing the distribution of monitoring points for the Adamboerskraal aquifer unit (WISH; Lukas, 2012).....	197
Figure 99: Time series graph of water levels for 37/2.	198
Figure 100: Time series graph of water levels for G33255 with cumulative deviation from mean.....	199
Figure 101: Time series graph of water levels for G33246 with cumulative deviation from mean.	200
Figure 102: Satellite image showing the distribution of a selection of monitoring points for the Grootwater aquifer unit (WISH; Lukas, 2012).	201
Figure 103: Time series graph of water levels for the four piezometers of G33331.	202
Figure 104: Time series graph of water levels for both piezometers of G33333 with cumulative deviation from mean.	203
Figure 105: Time series graph of water levels for G33304 with cumulative deviation from mean.....	204
Figure 106: Water levels for G33333-VL1, G33333-VL2 and G33304 with rainfall at Jakkalsfontein and Geelbek.	205

Figure 107: Time series graphs of water levels for G33333 and G33304 with CDM of rainfall.	206
Figure 108: Water levels for G33333-VL3 with the CDM curves of rainfall.....	207
Figure 109: Piper diagramme for the chemistry analysis of the cumulative rain gauges in the study area (generated with WISH; Lukas, 2012).....	208
Figure 110: Stiff plots for the chemistry results of the last data record for the cumulative rain gauges (generated with WISH; Lukas, 2012).....	209
Figure 111: Piper diagram for samples from the Berg River taken at the Kersefontein bridge (generated with WISH; Lukas, 2012).	210
Figure 112: Stiff diagram for the water chemistry at the Kersefontein bridge over the Berg River (generated with WISH; Lukas, 2012).....	210
Figure 113: Distribution of monitoring points on the Langebaan Road aquifer unit (42 of the 47 sampling points sampled regularly before 2010).....	211
Figure 114: Piper diagram for the monitoring points in the Adamboerskraal monitoring route (generated with WISH; Lukas, 2012).....	212
Figure 115: Stiff plots for the water quality of the geosites in the Adamboerskraal area (generated with WISH; Lukas, 2012).....	213
Figure 116: Satellite image showing water quality data points for the Adamboerskraal area.	214
Figure 117: Piper diagramme for the representative points in the Langebaan Road area (generated with WISH; Lukas, 2012).	215
Figure 118: Stiff plots for representative boreholes in the Langebaan Road aquifer unit (generated with WISH; Lukas, 2012).	216
Figure 119: Piper diagramme with representative points for the Elandsfontein aquifer unit (generated with WISH; Lukas, 2012).	217
Figure 120: Stiff plots for representative geosites for Elandsfontein aquifer unit (generated with WISH; Lukas, 2012).....	218
Figure 121: Piper diagramme for representative points in the Grootwater aquifer unit (generated with WISH; Lukas, 2012).....	219
Figure 122: Stiff plots for representative boreholes in the Grootwater aquifer unit (generated with WISH; Lukas, 2012).....	220
Figure 123: Stiff plots of the different aquifer units to give an indication of water quality type for each (generated with WISH; Lukas, 2012).....	224
Figure 124: Time series graph of streamflow generated in Hydras3 for gauge G1H013 upstream of G33323.....	226
Figure 125: Time series graph generated in Hydras3 showing the comparison of water levels in borehole G33323 and flow gauge G1H013.	227
Figure 126: Satellite image showing some of the wetlands, riparian zones and pans in the northern part of the study area (WC Dept.A, 2021).....	229
Figure 127: Satellite image showing some of the wetlands, riparian zones and pans in the southern part of the study area (WC Dept.A, 2021).....	230
Figure 128: Map of the Berg catchment area showing the possible extent of the West Coast Aquifer System in broken green line.	236
Figure 129: Map of the Berg catchment area with possible fault lines in broken green lines.	238
Figure 130: Conceptual cross section through Langebaan Road and Elandsfontein Aquifer Units (conceptual understanding; not to scale).....	241
Figure 131: Cross section through the Elandsfontein Aquifer Unit - a conceptual understanding (not to scale).....	244

Figure 132: Cross section through the Adamboerskraal and Langebaan Road Aquifer Units - a conceptual understanding (not to scale).....	245
Figure 133: Cross section through the Grootwater Aquifer Unit - conceptual understanding (not to scale).....	246
Figure 134: Changes in a meandering river over time and how this affects the deposition of sediments.	248
Figure 135: Cross section through the Langebaan Road and Elandsfontein aquifer units, taking the sedimentology into account (not to scale).....	250
Figure 136: Map showing the boreholes used in the two transects, as well as other boreholes of importance, i.e. the LRA wellfield boreholes. (Hopefield transect—yellow line; Darling transect—green line) (Vermaak and De Haast, 2013).....	252
Figure 137: Transect showing boreholes from the proposed Hopefield recharge area past the LRA wellfield with the latest monitoring data (Vermaak and De Haast, 2013).....	253
Figure 138: Transect showing boreholes from the proposed Darling recharge area past the LRA wellfield with the latest monitoring data (Vermaak and De Haast, 2013).....	253
Figure 139: Illustration showing the possible interaction between the current Berg River channel and the palaeochannel of the Berg River below it.....	255
Figure 140: Illustration to explain why both the upper and lower aquifer layers of the Elandsfontein aquifer unit responded to the abstraction at the Langebaan Road wellfield.....	256
Figure 141: Top layer (generated with WISH; Lukas, 2012).....	257
Figure 142: Three-dimensional model of the Lower Berg River aquifer system (generated in WISH; Lukas, 2012).....	258
Figure 143: Simplified cross-sections showing the different geological formations.....	259
Figure 144: Models of the West Coast Aquifer System, based on conceptual model.....	264
Figure 145: Boundary conditions and the model mesh: The Upper Model Surface. Red nodes indicate abstraction wells, black nodes represent transfer boundaries and blue nodes indicate constant head boundaries (DWAF, 2008).....	268
Figure 146: The twelve principles of groundwater management (Fourie, 2019).....	275
Figure 147: Illustration of the network of links between the 12 management principles.....	295
Figure 148: Flow diagram showing the different cycles for the adaptive management of groundwater developments.....	309

List of Tables

Table 1: The situation in South Africa compared to the OECD principles.....	39
Table 2: Application of the Reserve in a licence application (Vermaak, et al., 2019b).....	54
Table 3: Groundwater availability for part of the Berg River catchment area, according to GRAII (Vermaak, et al., 2019b).	56
Table 4: Groundwater resource availability for some of the Berg River catchment area according to NIWIS (Vermaak, et al., 2019b).	57
Table 5: Stress index levels using GRAII data.	64
Table 6: Groundwater mapping is always performed in 7 steps, but the scale of each step may vary between mapping areas (Miljøministeriet, Naturstyrelsen, 2012).....	72
Table 7: Factors that influence the sustainable management of groundwater (after Seward et al., 2006).....	77
Table 8: Mean Annual Precipitation at Calibration Rainfall Stations (Woodford, et al., 2003).	85
Table 9: Generalized geological formations of the study area (Theron, <i>et al.</i> , 1992; Roberts and Siegfried, 2014).....	109
Table 10: Correlation of the lithostratigraphic layers of the different aquifer units, using information from (K.M.G. Timmerman; Timmerman, 1985a; Timmerman, 1985b and Timmerman, 1988).....	110
Table 11: Evolution of fault zone with implication for hydrogeological classification of fault (Lin, et al., 2015).	118
Table 12: Summary of Drilling Results for DWAF's investigation of the Colenso Fault (after Parsons, 2012; Vermaak, et al. 2019).....	123
Table 13: Summary details of exploratory boreholes in the Kalbaskraal area, with one deep privately-owned borehole and yield testing (Parsons, 2005, 2012; Rosewarne, 2018; Vermaak, et al. 2019)	125
Table 14: Summary of SRK borehole details in the Chatsworth, Riverlands and Kalbaskraal areas (SRK, 1996; 1998; Vermaak, et al., 2019a).....	127
Table 15: Summary of exploration boreholes in the Klapmuts area (GEOSS, 2018; Peek, 2019; Visser, 2018). ...	128
Table 16: Groundwater Recharge per Groundwater Management Unit (after Woodford, et al., 2003; only relevant management units included).....	136
Table 17: Summary of the yield and storage potential for the Lower Berg River Aquifer System.....	140
Table 18: Summary of Groundwater Development Potential for the selected Target Areas – selection of sites (Woodford, et al., 2003).....	141
Table 19: Summary of rainfall stations in the study area with data records available.	171
Table 20: Recent recharge estimations (¹ Spannenberg, 2015; ² Ebrahim, 2015).....	174
Table 21: Results from PhreeqC modelling for the February 2008 sampling run for each of the monitoring points, with the major constituents in mol/ℓ, for the five constituents with the highest concentrations.	221
Table 22: EC values for Hopefield transect and Darling transect (Vermaak and De Haast, 2013).....	254
Table 23: Summary of input parameters (DWAF, 2008).....	268
Table 24: Susceptibility matrix (DWA, 2013a)	276
Table 25: Parameters that make up a groundwater resource monitoring programme (Fourie, 2019, adapted).	283
Table 26: Stakeholder analysis for the Lower Berg River Aquifer System.	290
Table 27: Action plan for the development of an adaptive management strategy, using the 12 management principles.	296

Explanation of Terms

<u>Term</u>	<u>Explanation</u>
Argillaceous	Comprising of clay, clayey. Shale.
Anastomosing	In the sense herein, a main fault plain that has branches that later re-join the main fault.
Arenaceous	Comprising of sand, sandy. Sandstone.
Brecciation	A zone of coarse and angular rock fragments cemented in a fine grained matrix, often associated with fault zones.
Calcrete	Calcrete, also called Hardpan, calcium-rich duricrust, a hardened layer in or on a soil. It is formed on calcareous materials as a result of climatic fluctuations in arid and semiarid regions. Calcite is dissolved in groundwater containing carbonic acid and, under drying conditions, is precipitated as the water evaporates at the surface.
Conglomerate	A rock comprised of coarse, rounded grains or pebbles contained in a finer-grained matrix.
Data loggers	<p>A number of data loggers were used to provide continuous hourly readings of water levels and rainfall. These include loggers produced by OTT, Eijgelkamp and Solinst.</p> <p>OTT HydroMet – German company producing data logging and telemetry equipment since 1873.</p> <p>Products:</p> <p>OTT Thalimedes – float-operated shaft encoder level sensor and logger; used for water level measurements and surface water; adapted for use in cumulative rain gauges in SA; out of production</p> <p>OTT Orphimedes – level sensor and logger using bubble pot; used for water level measurements in ground- and surface water; out of production</p> <p>OTT Orpheus Mini – water level logger with integrated pressure sensor and data logger for level measurements in surface and groundwater applications</p> <p>OTT CTD logger – logger with integrated pressure sensor and sensors for the measurement of EC and temperature in surface water and groundwater</p> <p>Hydras 3 – programme for the management of data loggers, stations and small measuring networks</p> <p>Solinst levellogger, barologger</p> <p>Eijgelkamp diver, baro</p>
Dolerite	A medium grained, dark coloured intrusive rock often in the form of dykes and sills.

Depocentres	Depocentre (or depocenter) in geology refers to an area or site of maximum deposition, or the geographic location of the thickest part of any specific geographic unit in a depositional basin. Within a basin, different areas receive different amounts of sediment through time, resulting in numerous depocenters.
Dyke	A steeply dipping/vertical sheet of usually igneous rock cross-cutting other strata.
Ferricrete	A recent-age surface deposit of gravel cemented by iron oxide.
Geosite	Groundwater related measuring point that includes boreholes, dug wells, springs, wetland, pans and rain gauges. Standard Geosite descriptors.
Hydraulic conductivity (K)	Describes the ease with which water can move through pore spaces or fractures.
Major aquifer	A highly permeable formations, usually with a known or probable presence of significant fracturing; may be highly productive and able to support large abstractions for public supply and other purposes; water quality is generally very good.
Minor aquifer	A minor aquifer is a fractured aquifer, or an aquifer that consists of potentially fractured rock that do not have a high primary permeability; it may also be other formations of variable permeability. The aquifer extent is usually limited and the water quality variable. Indications are that these aquifers seldom produce large quantities of water, but they are important for local supply and baseflow to rivers.
Mountain block	Area of topographically elevated and rugged terrain where soils and unconsolidated sediments are thin to non-existent, such that the shallow sub-surface is composed predominantly of bedrock; topographically and geologically distinct from adjacent lowland areas, which are relatively flat and underlain by thick unconsolidated to semi-consolidated sediments (“basin-fill”) that often form highly productive aquifers
Mountain front	Surface trace of the geologic contact between mountain block and adjacent basin-fill; linear feature delineated by intersection of two planar features: <ul style="list-style-type: none"> (a) Ground surface; (b) Subsurface geology contact between bedrock of mountain and adjacent basin-fill
Orogeny	A process where a section of the earth’s crust is folded and deformed by lateral compression to form a mountain range.
Plastic	In the sense herein, easily moulded or deformed without fracturing.
Porosity	Porosity or void fraction is a measure of the void spaces in a material and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0% and 100%. Strictly speaking, some tests measure the "accessible void", the total amount of void space accessible from the surface.
Quaternary Catchment / drainage region	A fourth order catchment in a hierarchal classification system in which a primary catchment (e.g., the Berg River) is the major unit.

Silcrete	A recent-age surface deposit of sand and gravel cemented by silica.
Synclinal	A type of folding with limbs on either side of an axial plane dipping inwards.
Transmissivity (T)	Transmissivity is the rate at which water passes through a unit width of the aquifer under a unit hydraulic gradient

List of abbreviations

AAU	Adamboerskraal Aquifer Unit
AR	Artificial Recharge
CDM	Cumulative Deviation from Mean
CSIR	Council for Scientific and Industrial Research
EAU	Elandsfontein Aquifer Unit
GAU	Grootwater Aquifer Unit
LAL	Lower Aquifer Layer
LBRAS	Lower Berg River Aquifer System
LRA ARS	Langebaan Road Aquifer Artificial Recharge Scheme
LRAU	Langebaan Road Aquifer Unit
mamsl	meter above mean sea level
MAR	Managed Aquifer Recharge
MBR	Mountain Block Recharge
MFR	Mountain Front Recharge
NEMA	National Environmental Management Act of 1998 (Act 108 of 1998)
NIWIS	National Integrated Water Information System
NWA	National Water Act of 1998 (Act 36 of 1998)
OECD	Organisation for Economic Co-operation and Development
SAWS	South African Weather Services
TMG	Table Mountain Group
UAL	Upper Aquifer Layer
WA	Water Act of 1956 (Act 54 of 1956)
WAAS	Water Availability Assessment Study
WCDM	West Coast District Municipality
WC WSS	Western Cape Water Supply System
WSA	Water Services Act of 1997 (Act 108 of 1997)
WTW	Water Treatment Works
WWTW	Wastewater Treatment Works

Chapter 1: Introduction



Maintenance at BG00136 (25 August 2010)

When working on a project or study area boundaries are set for the project or study area. This is to enable one to work on a contained unit, to make it slightly easier for ourselves. We tend to oversimplify the systems contained in our study area, try and break it up in smaller units, try to study one factor or characteristic at a time. In the back of our mind we know that there are outside influences and forces that have the ability to change the situation in our box that we have created for ourselves and we try and rationalize that their influence on the system is negligible or can be included in the study at some later stage. We try our best to understand our study area with the little bit that we have gained from measurements – monitoring – and observations, and the work of those who have gone before us, that we forget about the factors outside our boundaries. Sometimes we get bogged down in the details of the system, trying to understand each detail and how it fits together, what its influence could be on the system. The human mind, as wonderful as it is, is limited in its ability to process and understand all the complexities of the natural world. Then, once in a while, something happens – a piece of information comes to your attention, you

have an interesting conversation, a presentation on scientific research – that awaken you to the fact that you may have missed to point in its entirety by focusing too much on the details. This had been the constant experience while working on this project, even before a formal proposal had been drafted. What is presented in this thesis is the culmination of years of work by various individuals – all with different goals in mind – and the dedication of a number of government officials that went out regularly to do the monitoring in the area – in rain, sleet, hail or frost, as well as the burning heat in late summer.

It would have been the ideal to have all the puzzle pieces together and in the right place, but it is not always possible in a natural system. There are high levels of uncertainty, and it is not always possible to fully understand key elements that is crucial to the proper management of the groundwater resource. It was while contemplating the Lower Berg River Aquifer System with all of its complexities that the need for a comprehensive management plan realized. This is a necessity to manage the resource sustainably for all the competing water uses in the area despite the fact that the scientific understanding about the system may be lacking. The recent drought in the Western Cape highlighted the need for such a management plan that could contribute to ensure the protection of the resource and the availability of groundwater for its users (including the ecology), well into the future despite climate change predictions for the west coast of the Western Cape.

1.1 General Research Statement

The town of Saldanha and the surroundings always had a challenge when it came to water availability. There are no significant rivers in the area – the nearest significant, perennial river being the Berg River. The rainfall is low and unreliable, the soil is sandy and there are many sunny and windy days that increase the possibility of evapotranspiration. The lack of sufficient water was the main constraint to development in the area for almost three centuries. Very little of this history has been recorded (Visser, et al., 2008), but is an important part and underlines the importance of finding a sustainable water resource that need to be managed carefully.

Visser et al. (2008) provides a brief overview of the water supply history of the Saldanha area. Sir John Barrow identified two springs near Langebaan, on the southern end of Saldanha Bay during his travels around 1797 – 1798. Major J.G.W. Leipoldt did a survey on the water shortage at the village of Saldanha in 1917 and found that most of the water sources was at the southern end of the bay, near Langebaan, while the best landing places was near Hoedjes Bay. Shallow wells were dug in the sand around Langebaan and at one time these wells produced 14 000 litre of fresh water per day for use by the whaling company. Rainwater harvesting was also used for water supply purposes. This was still the situation in 1939 when the Second World War broke out. Saldanha Bay was identified as of strategic military importance and a military presence was established to defend the bay. Harbour facilities were developed in 1941 and it soon became clear that a more sustainable water source would be needed. Circle engineer E. Fincham led the project that was responsible for the pipeline from the Berg River to Saldanha, with the Besaansklip reservoir, on the farm Vergelegen (Figure 1). This water supply was initially only available for military use but became

available for domestic use after the war ended. This supply allowed the towns in the area to grow, and with the harbour expansions to allow for export of ore, the possibility existed for industrial development. It is thus clear from the above why it would be important for the area to investigate all possible water sources.

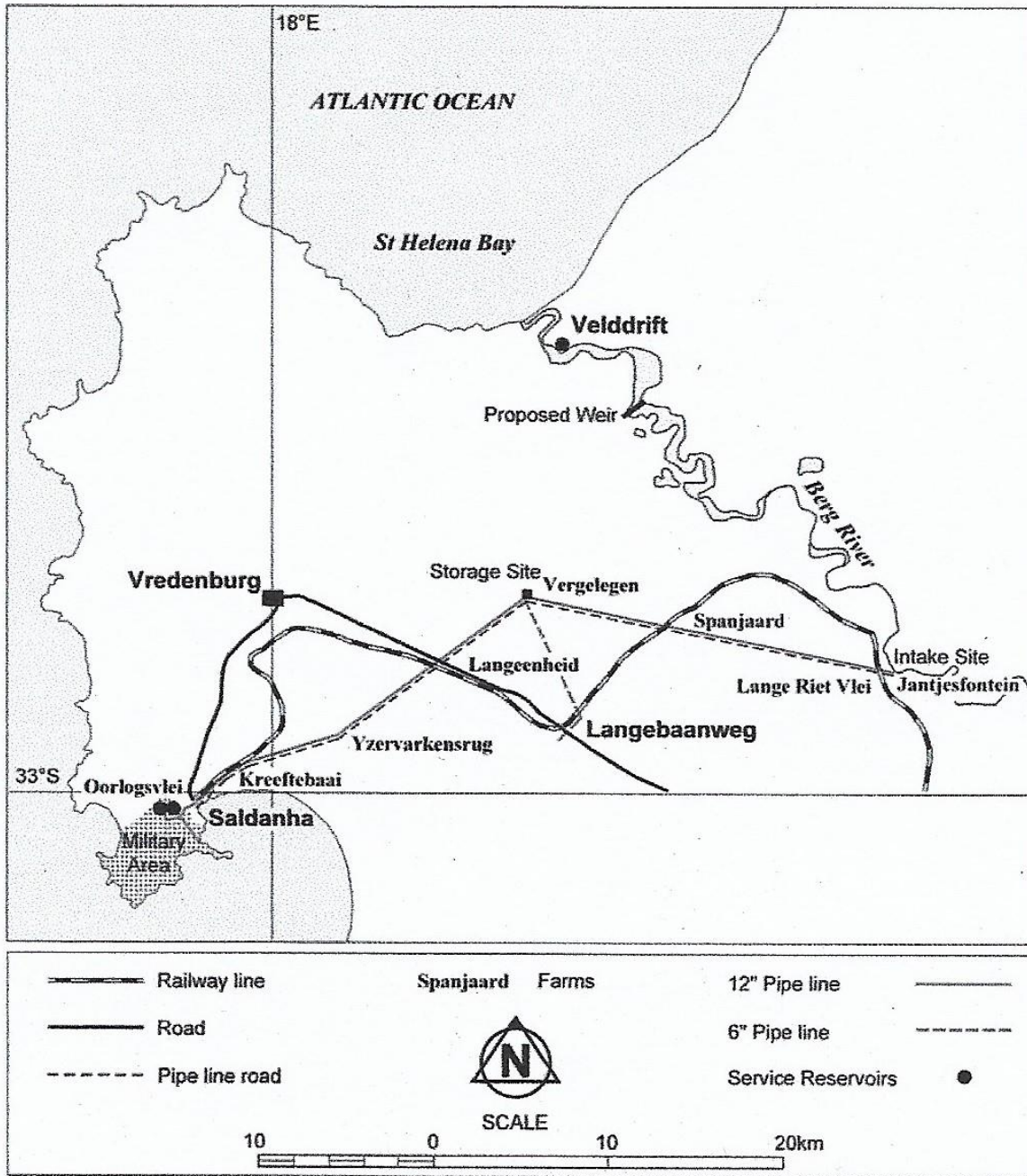


Figure 1: Berg River/Saldanha Bay pipeline in 1942/43 (Visser, et al, 2008).

The Berg River has its limitations as well, since the water quality in the lower part of the river is variable as a result of tidal influences. The tides can move up to 25km inland and only releases from the Theewaterskloof dam made it possible to abstract relatively fresh water from the Berg

River pump station, as it pushed the tidal zone seawards. The river also receives treated effluent discharge from the wastewater treatment works from a number of municipalities along the way, as well as agricultural return flows. This adds to the nutrient and salt load in the water that reaches the Withoogte water treatment plant that provides potable water to the Saldanha Bay Local Municipality. The recent drought has also shown the vulnerability of the Berg River to droughts and the potential effects of climate change, as the river were in places reduced to puddles (“kuile”). It is a clear indication that the Berg River water is overallocated and management of the resource is unsustainable. Alternative water resources are thus urgently needed, and groundwater is one of the best options under consideration for the area.

Groundwater development for municipal supply has been fairly slow in this part of the Berg River area. Perhaps it was as a result of the earlier experience with the use of groundwater in the area, it was not really seen as a viable option early on. The words of Enslin (1964) indicate the fact that there was a realization in the early 1960s that very little is known about our groundwater resources:

Our present knowledge of the ground-water occurrences of the Republic – the characteristics of the aquifers, the quantities of stored groundwater, the annual recharge of the supplies, the quality of the water and the methods of tracing and developing the supplies – is not nearly sufficient to enable us to assess the available supplies and their safe yields to serve as a basis for the planning and control of the conservation and utilization of those resources.

Subsequent investigations have added to our understanding of groundwater, but Enslin’s words is still applicable to the current situation with regards to groundwater due to the high level of uncertainty with groundwater systems. It is interesting to note that the Interdepartmental Committee on Hydrological Research was established at about the same time that Enslin wrote his report (Vermaak, 2013). It would seem that there had been a great interest to study the water resources of the country at that time. Coastal aquifers have not received as much attention in South Africa as the fractured aquifers, as it only makes up a small percentage of the groundwater systems in the country. They are, however, very important locally and are very vulnerable and susceptible to the impacts of human activities.

The investigation into the groundwater potential in the Western Cape began in the middle to late 1960s. Exploration for water and mineral resources in the West Coast – the area between the Modder River and Velddrif began in the early 1970s with work by the South African Geological Survey (Department of Mines). The Department of Water Affairs (Division of Geohydrology) took over the West Coast projects after 1977. Various geophysical prospecting methods were used between 1974 and 1977, including refraction seismic and gravimetry (Botha and Thompson, 1977). The geophysical methods failed to give an indication of the thickness of the Cenozoic sediments since it was difficult to distinguish between the unconsolidated deposits and the weathered bedrock materials. The cable tool percussion boreholes had, however, provided valuable sedimentological, geological and hydrogeological information (Timmerman, 1988).

Artesian boreholes, yielding water of a good quality, were drilled in the Langebaan Road area during this time. This led to the recognition of the possible groundwater potential of the area (Timmerman, 1988). The Saldanha Subterranean Government Water Control Area (SSGWCA) was declared by Government Gazette in September 1976 (RSA, 1976) to protect the groundwater resources for future municipal supply. A second reason for the declaration of the SSGWCA was to minimize the interference during further investigations into the geohydrology of the area (Vandoolaeghe, 1983; Timmerman, 1988).

The objectives of further work in the area included (i) the description of the primary aquifer system in the Lower Berg River area and (ii) the determination of the groundwater exploitation potential of the area with the possibility of future industrial developments. Further work included geo-electrical soundings (Smith, 1982), cable tool percussion and mud rotary drilling, geophysical borehole logging, pumping tests, slug tests, hydrochemical sampling and water level monitoring (Timmerman, 1988).

The Langebaan Road wellfield was developed in 1998 to provide additional water to Saldanha Bay Local Municipality for the needs of Saldanha Steel industrial development. The wellfield became operation in December 1999 and had been operational since then with only a few breaks in abstraction to allow for the repairs of pumps and as a result of vandalism. It has thus shown that groundwater can be a reliable resource.

Rapid development in the Saldanha area of the residential, commercial and tourist sector caused the realization that the available water resources was inadequate to meet the requirements of the area, with the demand exceeding the authorized volume in 2003, despite a saving of 10% through water conservation and water demand management. A large-scale investigation was launched by the West Coast District Municipality (WCDM) and a number of additional sites were identified for potential groundwater developments (Woodford, et al., 2003). None of the proposed developments were taken further and the WCDM exceeded their authorized allocation from the Western Cape Water Supply System for a number of years (DWS, 2015).

Artificial recharge (also known as Managed Aquifer Recharge) pilot tests were carried out in 2008 and 2009 to test the effectiveness of augmenting groundwater resources in this system. The results were disappointing, but it confirmed that it would be possible to store additional water within the aquifer for later use. It also highlighted gaps in the scientific understanding of the system and showed that it would be necessary to develop a better conceptual model for the Lower Berg River Aquifer System.

The need for a follow up project was identified and it was included in the Reconciliation Study for the Western Cape Water Supply System (WC WSS) (DWS, 2015). The WC WSS was developed to manage the water supply from the Berg River and associated infrastructure. It is made up of five major dams – Voëlvlei, Wemmershoek, Berg River, Steenbras Upper and Lower, and Theewaterskloof – that provides water to municipalities (Cape Town, Stellenbosch, Drakenstein, Swartland, Saldanha, Bergrivier and Theewaterskloof) and agriculture. The system is managed

jointly by the Department of Water and Sanitation, the municipalities and agriculture. The system is currently overallocated, as mentioned above, but the interventions that was identified in the WC WSS Reconciliation Strategy was not implemented in time to prevent the impacts of the recent drought. Most of the interventions had to be fast tracked. One of the interventions identified was the Langebaan Road Artificial Recharge Scheme that was meant to augment the water supply to Saldanha Bay Local Municipality, and thereby reduce the stress on the WC WSS. Figure 2 shows how the intervention of storing excess winter water in the Langebaan Road Aquifer Unit (ASR on the image) would contribute to the water resources available in the WC WSS. The report was completed in the initial stages of the drought, before the implications and extent of the drought was clear. This graph also does not include environmental releases and the effects of water loss through invasive alien trees in the catchment area (DWS, 2015).

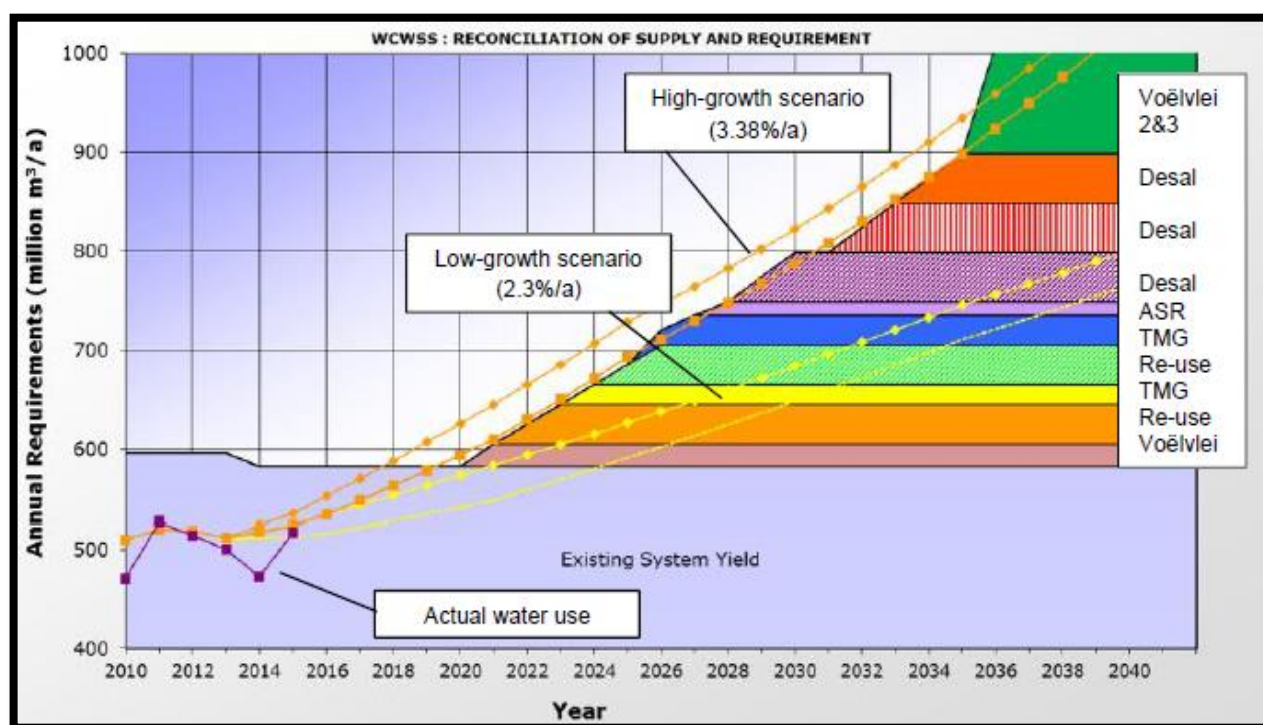


Figure 2: Reconciliation of water supply and requirement for the Reference Scenario for the WC WSS before the drought (DWS, 2015).

Figure 3 show the medium to long-term reconciliation options that include climate change and the effects of alien vegetation. It also shows the effect of the recent drought on water use out of the WC WSS. There was a huge drop in water use from 2015 to 2018 as a result of water use restrictions, adjusted tariffs and behavioral changes. Predictions are that the water use will recover to follow the same trend as before the drought, resuming the previous trends by 2023.

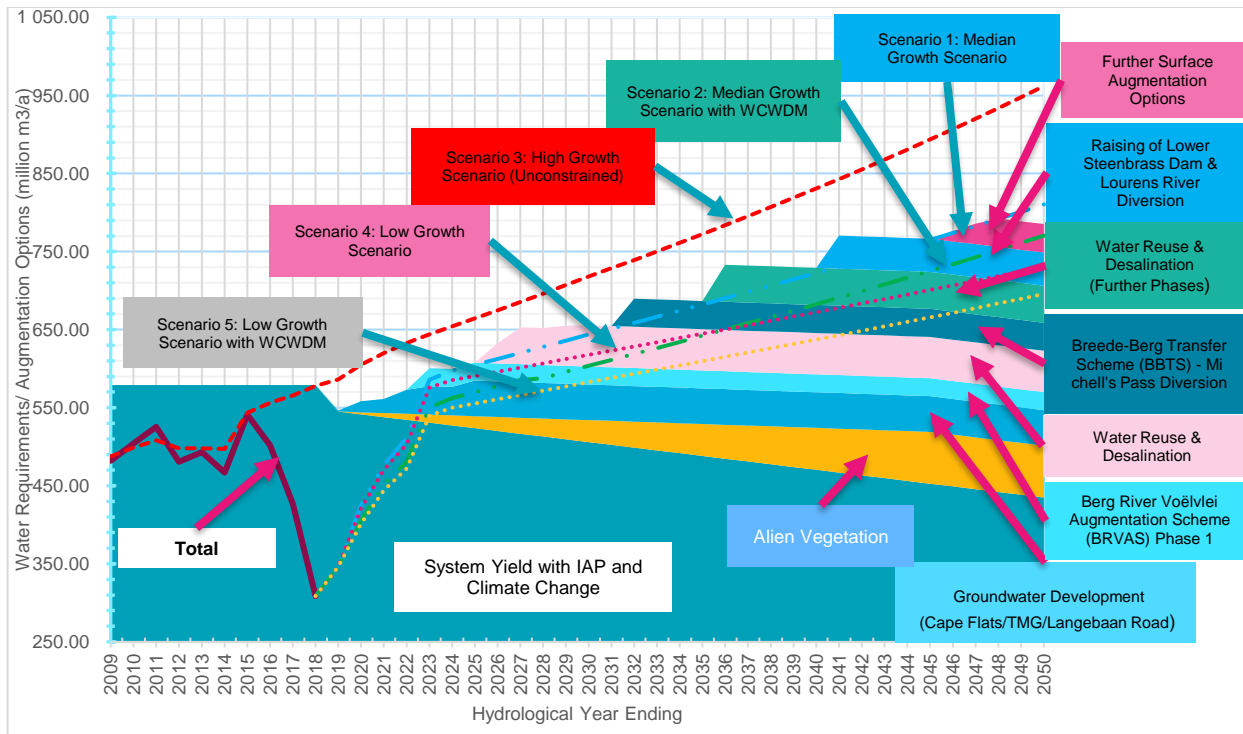


Figure 3: Medium to long term reconciliation options to manage the water balance of the WCWSS, taking the potential impacts of climate change into consideration (DWS, 2019).

The Saldanha area has also been earmarked for industrial development because of the natural harbor, with the Saldanha Industrial Development Zone and other developments. The need for water would thus increase as the developments take place, with water required for industrial use and domestic use because of the increase in population as the job opportunities increase. The scarce resource will have to be managed more effectively, efficiently and equitably to ensure sustainability between the increasing pressure of the growing number of competing water users of the system.

1.2 Problem statement

Water scarcity hampered the development of the Saldanha area, and this problem increased as the population increased, and the number of industries grew. The water scarcity is partly the result of the climate in the area – low rainfall, high temperatures in summer and high potential evapotranspiration as a result of the high temperatures and wind. Climate change models predict that the area will become drier as a result of lower rainfall (or less consistent rainfall), and higher temperatures. A second factor that have an impact on the water scarcity in the area is the fact that most of the rivers in the area is non-perennial, except for the Berg River. The Berg River is subject to pollution by agricultural return flows and treated effluent from wastewater treatment works that are returned to the river, as well as the tidal zone that stretches 25km inland. This affects the usefulness of the water for municipal supply. The groundwater systems in the area are an additional resource that is available for municipal supply, but the aquifers are linked to important sensitive ecosystems. It is thus important to have a conceptual understanding of the water issues

in the area in order to improve water management of the whole system to ensure sustainable ecosystems and assurance of supply to the municipalities.

1.3 Research aim and objectives

- The research aim is to provide an action plan with relevant principles and site specific conditions to enable the relevant stakeholders to develop a comprehensive management strategy for the Lower Berg River Aquifer System that is based on the current understanding of the geohydrology of the area, using international best practice and the legislative framework that is available.

. The following objectives needs to be achieved, in order to achieve this goal:

- The research will develop a data-supported conceptual model that describes groundwater processes for a coastal aquifer in a semi-arid environment.
 - It will be done by evaluating all available information in reports and other publications (Chapter 3);
 - Analyzing the data that has been collected, mostly by DWS during their monitoring of the area, with various statistical methods (Chapter 4); and
 - Collating all the available data and information into a conceptual model that will on a local and regional scale the observations that has been made (Chapter 5).
- It will evaluate different groundwater models to determine their ability to replicate the Lower Berg Aquifer System as example of a coastal aquifer in a semi-arid region successfully (Chapter 6).
- Finally, it will develop an action plan using the framework for groundwater management strategies for the development of a comprehensive adaptive management strategy that can be used for coastal aquifers with the relevant stakeholders in the semi-arid areas of Southern Africa. This will be done by
 - Evaluating international best practice, principles and legislation and compare it to the South African legislative framework and situation (Chapter 2);
 - Evaluating the tools provided by the South African legislative framework to sustainably, efficiently, effectively and equitably manage groundwater resources (Chapter 2);
 - Developing an action plan for the development of a comprehensive adaptive management strategy that can be adapted to site specific coastal aquifers in the semi-arid areas of South Africa that is summarised in a table and with a flow diagramme (Chapter 7).

1.4 Research statement

- How do you manage an extensive coastal aquifer system sustainably using available data, current understanding, adaptive management tools, international best practice and available legislative framework?

1.5 Thesis structure

An attempt has been made to structure the thesis in a manner that will lead the reader through the subject matter in the most logical manner.

- It will begin with the theoretical framework as contained in Chapter 2 where it looks at coastal aquifers and its specific characteristics using a number of examples. It will then look at groundwater management and the different methods that can be used to ensure sustainability of the resource.
- The Study Area will be described in Chapter 3 and it will look at all the factors that may have an influence on the geohydrology of the area. This includes the Topography, Geology, Climate, Vegetation, Land Use and the different water resources that need to be considered in the management of the resource in the study area.
- Chapter 4 will look at the geohydrological characteristics of the area that will feed into the Conceptual model. It will look at the monitoring data which includes water levels, rainfall and water quality using statistical analysis.
- The first objective of developing a conceptual model will be the subject of Chapter 5,
- while the evaluation of the existing models (objective 2) will be discussed in Chapter 6.
- Chapter 7 will discuss the Management Strategies (objective 3).
- The Discussion will be done in Chapter 8 with the
- Conclusion and Recommendations in Chapter 9.

It is hoped that this work will add to the understanding of coastal aquifers in the Southern African region and provide strategies for the management of the groundwater resource stored in these aquifers in a sustainable manner.

Chapter 2: Theoretical Framework



Wind pump and wind turbine on the Farm Koperfontein, just outside Hopefield (14 October 2013)

Enslin (1964) expresses the concern about the impact of groundwater users on the sustainability of groundwater supplies. There is a call for investigations to be conducted into whether it is desirable to abstract large volumes of groundwater for irrigation, linked to the lowering of the water table and the subsequent decreases in the availability of groundwater. It is interesting to note that bulk supply for municipal and industrial use had not been included at this stage. It would seem that this call for investigations into groundwater availability sparked large scale investigations when looking at the activities of the Department of Water Affairs (now the Department of Water and Sanitation) and the Geological Survey in the late 1960s and early 1970s. These investigations eventually lead to GRAII and the Hydrological Map Series in the early 2000s, both products that are being used extensively by the groundwater community. It would, however, seem that this has all been a theoretical academic exercise, that looked at the potential and occurrence of groundwater but not the sustainability thereof as well as the protection of the resource. This last part has become increasingly important, as the most recent drought has seen the perceived value of groundwater rise to the level where almost everyone sees it as the solution to the water supply problem. Once again, it seems that the link groundwater plays in the hydrological cycle and the fact that it too is dependent on rainfall, albeit at a delayed response.

This chapter will briefly look at the characteristics of coastal aquifer, as well as examples of coastal aquifers around the world. Emphasis has been placed on coastal aquifers with similar lithology and climate, in order to compare them with the study area. A brief summary is then presented about coastal aquifers in South Africa with more detailed information about the coastal aquifers along the West Coast of the Western Cape. The chapter then moves to the topic of groundwater management, where it looks at international principles and legislation, the South African legal framework and then at adaptive management as a strategy for the management of coastal aquifers.

2.1 Coastal Aquifers

An aquifer is defined as a formation that contains enough water in the saturated permeable material in order to make it economically viable to abstract the water from wells, boreholes and springs (Driscoll, 1976). A coastal aquifer is thus a water-bearing geological formation that is hydraulically connected to the sea (Johannes, 1980). According to Campbell, et al., (1992) coastal aquifers are unconfined, but the reality is that it is possible to get semi-confined to confined aquifers in a coastal aquifer.

Coastal aquifers usually consist of unconsolidated to semi-consolidated deposits of sand, gravel and pebbles. The interstices are still intact, and the form has not changed as a result of compaction, recrystallization or cementation (DWA, 1986). The coastal aquifers are mostly composed of Cenozoic deposits from the Cretaceous Period, especially the Tertiary and Quaternary Eras. Narrow strips of alluvium in and along rivers, coastal sand deposits, clay and calcrete lenses all from part of these sediments (Vegter, 1987). Unconsolidated dune sand, fluvial sand, estuarine sand, or a combination thereof are deposited on basement rock (Rust, 1987). According to Tinley (1985) it may be linked to sea level fluctuations but may also be more recent aqueous or aeolian depositions. The thickness of the deposits may vary between a few meters to more than 50m (Rust, 1987) It is estimated that coastal aquifers in South Africa can yield from 5% to 30% of the water stored in the aquifer (DWA, 1986), but that the supply would be variable.

The water quality of the groundwater in coastal aquifers are dependent on recharge volume and rate, the characteristics of the aquifer sediments, the exchange between the bedrock and the overlying deposits, the residence or response time, depth to water table, abstraction and pollution. Water quality will be changed through geochemical processes. The salinity of groundwater is a function of evapotranspiration, seawater intrusion, salt leaching, weathering and erosion of the parent material, selective retention of salts by plants, the physical properties of the substratum and the retention time in the aquifer (Campbell, et al., 1992).

Coastal aquifers are not just important as a water resource but plays an important role in the functioning of associated ecosystems. Bokuniewicz (1980; as cited in Campbell, et al., 1992) has estimated that coastal aquifers may contribute up to 65% of the total freshwater inflow into the sea. Marsh systems need groundwater from coastal aquifers to maintain the coastal system biodiversity. Pollution in a coastal aquifer, reduced outflow and changes in the nutrient inputs to the coastal ecosystem and other groundwater dependent ecosystems can cause a shift in the

ecological balance (Campbell, et al., 1992). Groundwater of coastal aquifers discharging directly into the oceans, at an estimated global rate of 2 383km³/annum also transports 1 293million tons of dissolved solids to the sea on a yearly basis (Zektser and Dzhamalov, 1988). The inflows of dissolved matter are equivalent to 52% of those discharged by streams into the oceans (Zektser and Everett, 2004).

The water resources in coastal aquifers are not unlimited. The Netherlands experienced seawater intrusion due to overabstraction in the 1930s and began implementing artificial recharge through dune infiltration in the 1950s to maintain the saltwater freshwater balance (Piet and Zoeteman, 1980). Dune infiltration has since become an accepted method for the storing and purifying of surface water (Campbell, et al., 1992).

2.1.1 Coastal aquifers from other parts of the world

Europe, with its long continental and island coastline have numerous coastal aquifers. Some of these aquifers are relatively small in size, but they are crucial in supplying freshwater for human needs. Custodio (2010) divided the coastal aquifers into deltaic areas, detritic coastal formations and carbonate coastal massifs, in addition to small islands. The first two types of coastal aquifers are normally associated with river systems. This includes the deltaic areas associated with the Rhine-Meuse in the Netherlands, the Aveiro in northern Portugal, the Guadalquivir in southwestern Spain, the the Ebre and Llobregat in Catalonia, northern Spain, the Rhone in southern France, the Po in northeastern Italy, the lower Tagus River in Lisbon, Portugal and the Thames at London, southeastern UK. These aquifers formed under similar conditions as the West Coast Aquifer System, as it was formed during a time when the sea-level was much lower, resulting in rivers cutting deep channels into the hard rock formations of the area, which was later filled with sand, gravel and clay of fluvial, estuarine, marine and aeolian origins. These sediments may be permeable to very permeable, with water of variable quality, depending on the type of sedimentation that occurred. Coastal aquifers in the northern half of Europe were formed by deep glacial valleys that was filled with glacial and fluvioglacial deposits of gravel, sand, and clays. These aquifers are dominant in Jutland, Denmark, the coast of northern Poland, northern Germany, and the Netherlands (Custodio, 2010) The climate of the Mediterranean area will be similar to the West Coast, with winter rainfall and dry, hot summers.

Western Australia is similar to the West Coast of South Africa in a number of ways, except for its climate classification. The Köppen Classification classify the area as 'temperate' in the south and 'sub-tropical' in the north (Bureau of Meteorology, 2009), whereas the Western Cape is semi-arid in the south and arid in the north. The region has a Mediterranean climate with 80% of long-term mean annual rainfall in May to October. The topographical features of the area consist of coastal plains with an elevation of less than 150m AHD (Australian Height Datum). An escarpment separates the coastal plains from the inland plains that reach an elevation of 350m AHD (Emelyanonova, et al., 2013). The Gngangara Groundwater Mound is an important source supplying groundwater to the city of Perth and for irrigated agriculture. It also maintains wetland ecosystems in the area. The aquifer is mostly unconfined, but confined systems are present. The superficial

aquifer is a complex, unconfined, multilayer system (Davidson, 1995) that is separated from the shallow confined aquifer (Leederville aquifer) by a confining layer. Reduced rainfall thus has a major impact on the water levels in the groundwater system, with a fall in water levels recorded since 1969. This decline has also affected wetland systems. Additional factors that may have an impact on water levels is abstraction for the growing population of Perth and agriculture (from both the superficial and confined aquifers), evapotranspiration from pine plantations (which are affected by the establishment, thinning and clearing of the plantations), bushfires, and climate variation (Yesertener, 2002; 2005; and 2008). The climate in the southwestern Australia has become drier since 1975 (1969 according to Yesertner (2008)), and it is expected to become even drier in future (CSIRO, 2010, Petrone, et al., 2010; Ali, et al., 2012a; Emelyanov, et al., 2013).

Coastal aquifers can also be found along the coast of South America. Bocanegra, et al. (2009), divides these aquifers into four hydrogeological provinces where the aquifers range in size from small, but locally important to slightly used continental aquifers. The Atlantic Coastal Hydrogeological Province stretches from Uruguay in the south to Colombia in the north, with unconsolidated to semi-consolidated aquifers of alluvial, fluviomarine and aeolian Cenozoic sediments with fair productivity (Lucena, et al., 2004; Bocanegra, et al., 2009). The Andine-Pacific Hydrogeological province can be found along the coast of Colombia, Ecuador, Peru and Chile and consist of small to medium aquifers made up of alluvial and sedimentary formations of continental detrital compositions. The Romeral basin in the north-central area of Chile is one example of the coastal aquifers in this area. It is an unconfined gravel and sand aquifer, with rainy winters and hot, dry summers (Squeo, et al, 2006). The Pantanal-Chaco-Pampean Hydrogeological Province is formed by the central coastal strip of Argentina with a wide variety of hydrogeological conditions. The Patagonia Hydrogeological Province is the fourth area and is found along the southern coast of Argentina (Bocanegra, et al., 2009)

California has a long coastline of almost 1800km and is densely populated. The coastal area of California was divided into four hydrologic regions (HR), i.e., the North Coast, San Francisco Bay, Central Coast and South Coast (Hoover, et at., 2017). The North Coast is the least populated, with 63 identified groundwater basins, of which two is shared with Oregon. This area receives the greatest amount of precipitation in California. Arcata is a part of the Eureka Coastal Plain groundwater basin and is underlain by alluvium composed of clay, gravel, sand, and silt (Evenson, 1959; CA DWR, 2013b; Hoover, et at., 2017). Groundwater is mainly used for agriculture and domestic needs. The San Francisco Bay HR is the smallest but has the second highest population. It imports about 70% of its water with only about 30% coming from local resources (CA DWR, 2013c; Hoover, et al., 2017). There are 28 groundwater basins in the area, but groundwater use in the area is only about 5% of the water used in the HR (CA DWR, 2003; Hoover, et al., 2017). Groundwater issues in the area includes land subsidence as a result of groundwater abstraction in the Santa Clara groundwater basin. There is also a potential for pollution from wastewater treatment systems in the Stinson Beach area (de Sieyes, et al., 2008; Hoover, et al., 2017). Stinson Beach is a small coastal community that is close to a groundwater system that is an unconfined

aquifer composed of beach and dune sands. The area has a Mediterranean climate with the majority of rain falling between October and April (de Siewes, et al., 2008; de Siewes, 2011; Hoover, et al., 2017). The Central Coast HR has 50 identified groundwater basins, with high reliance on groundwater. Groundwater use is at about 80%, as it is used for domestic, municipal and agriculture (CA DWR, 2013a; Hoover, et al., 2017). The area receives moderate rainfall, with the economy dependent on agriculture and viticulture (CA DWR, 2003; CA DWR, 2013a; Hoover, et al., 2017). Environmental issues include groundwater overdraft, sea water intrusion, water quality degradation, and flood risks (CA DWR, 2013a; Hoover, et al., 2017). The South Coast HR is the most populated part of California and thus also the most urbanised (CA DWR, 2013d; Hoover, et al., 2017). A number of 56 groundwater basins was identified in the area, with groundwater abstraction in the area taking place for more than a century. Sea water intrusion has been documented with the result that the coastal aquifers are highly managed, with sea water barriers in a number of places. Malibu Lagoon is a small residential community on the Malibu Creek Watershed that drains the Malibu Lagoon. The lagoon is an ephemeral water body with brackish water. The berm is breached during the winter, causing a direct connection with the ocean (Ganguli, et al., 2012; Hoover, et al., 2017). The Malibu groundwater basin is a relatively small aquifer that is predominantly alluvial, composed of silt, clay, sand, and gravel (McDonald Morrissey Associates Inc., 2014; Hoover, et al., 2017). Precipitation occurs mainly in winter between November and March. Groundwater is not used for public supply. Groundwater issues in the area include contamination, mainly from wastewater treatment in the form of septic systems and sea water intrusion (Izbicki, et al., 2012; Izbicki, 2014; McDonald Morrissey Associates Inc., 2014; Hoover, et al., 2017).

2.1.2 Coastal aquifers in South Africa

Enslin (1964) stated groundwater is the most difficult to understand and assess because it is not visible. Boreholes serve as a window into the subsurface giving us some indication of the groundwater resources. A concerted effort had been undertaken to get a better understanding of the groundwater resources in South Africa after the publication of Enslin (1964). This can be seen from the number of groundwater exploration projects that had been done in the late 1960 and onwards. This includes the work done by Timmerman in the early 1980s on the Lower Berg River Valley aquifer system (Timmerman 1985a & b). This study uses the name that Timmerman gave to the aquifer system, rather than West Coast Aquifer System, to prevent confusion with other coastal aquifer systems along the western coast of the Western Cape.

The most comprehensive work on coastal aquifers in South Africa, was that by Campbell, et al. (1992), where the report focused on unconfined aquifers. Twenty-four major coastal aquifers were identified along the South African coast, with a combined surface of 29 600km². Figure 4 shows the distribution of the coastal aquifers and provides an indication of its geology, based on the work of Roberts, et al (2006). Figure 5 provides the surface area of each of the coastal aquifers as delineated by Campbell, et al. (1992). Coastal aquifers may only make up less than 20% of the surface of South Africa, but they are important locally.

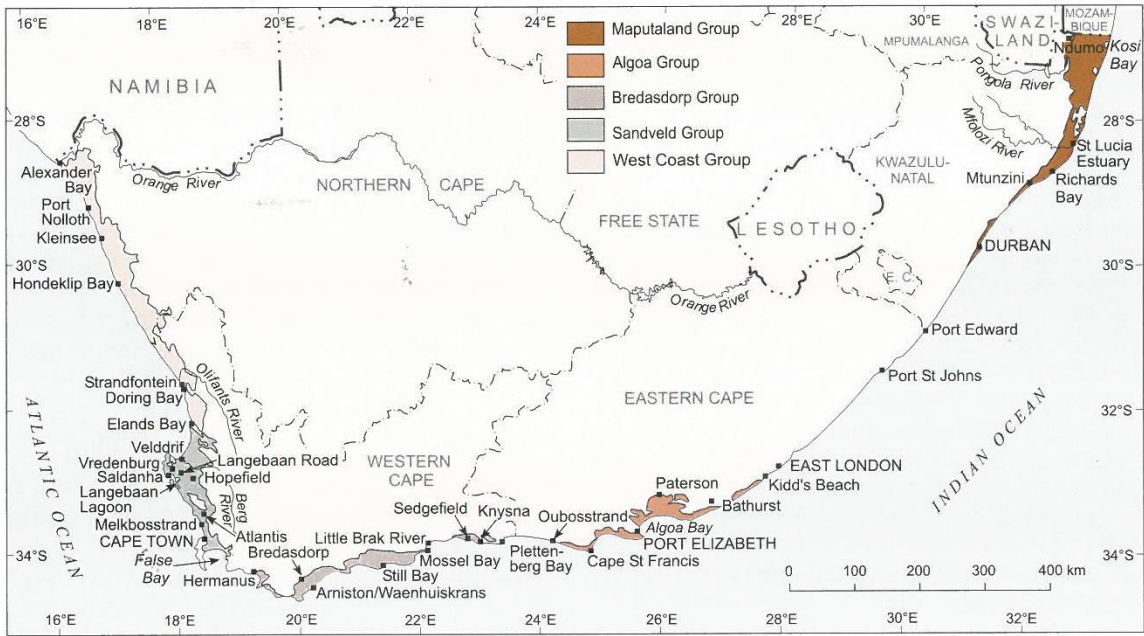


Figure 4: Distribution of coastal Cenozoic sediments in South Africa (Roberts, *et al.*, 2006).

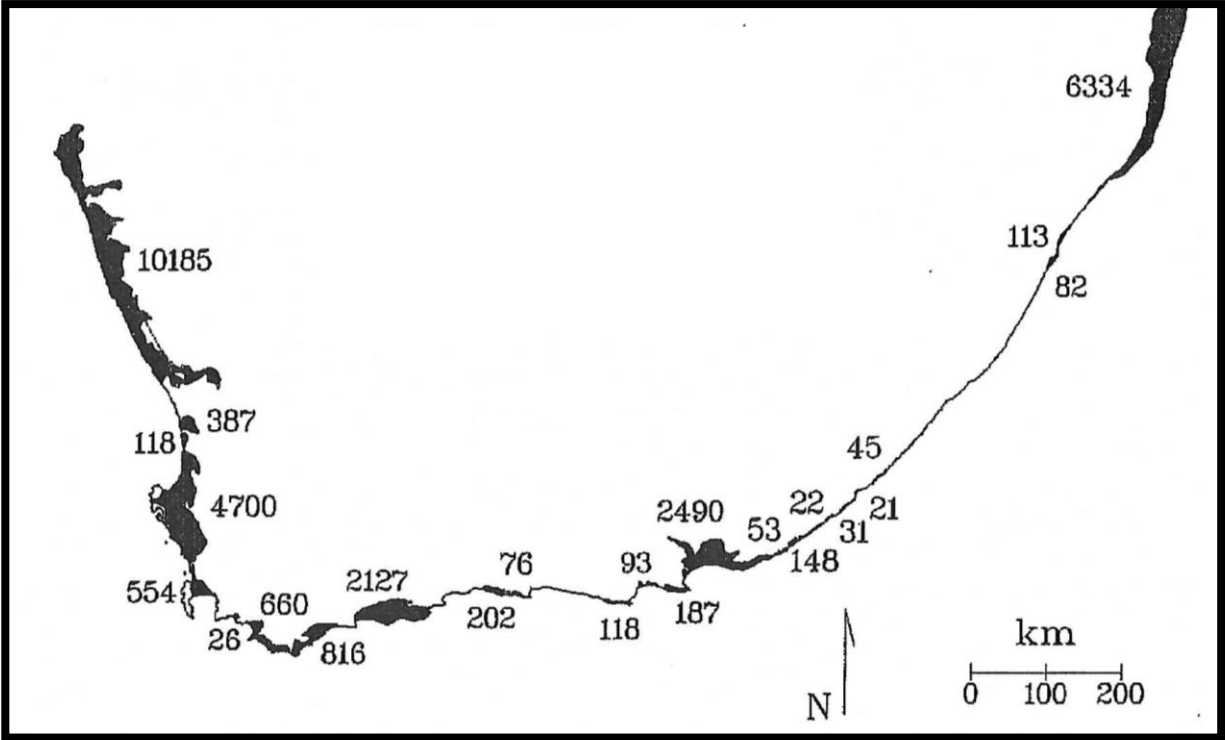


Figure 5: The Cenozoic deposits of South Africa (after Dept. Mineral & Energy Affairs, 1984) used for the identification of the boundaries of coastal aquifers. Their surface area is given in km² (Campbell, *et al.*, 1992).

A number of coastal aquifers occur along the West Coast of the Western Cape. These aquifers are the Cape Flats aquifer, the Atlantis aquifers (Witzand and Silberstroom), the Lower Berg River

Aquifer System (or West Coast) and the Sandveld aquifers (e.g., Verlorenvlei, Wadrif, Graafwater, Strandfontein). Several communities are wholly or partially dependent on these coastal aquifers for their water supply, including Strandfontein, Doringbaai, Lambertsbaai, Elandsbaai, Dwarskersbos, Langebaan, Yzerfontein, Hopefield, Atlantis and Mamre (Kok, 1990).

The Sandveld aquifers consist of Cenozoic deposits of the Sandveld Group in palaeo-valleys and local depressions that were more susceptible to weathering and erosion. The thickness of the deposits is controlled by the basement topography (Nel, 2009). The valleys tend to follow northwest trending faults that seem to control the courses of the major rivers in the area, i.e., the Jakkals, Langvlei and Verlorenvlei Rivers. The sand filled valleys make it difficult to determine the fault zone damage and the possible stratigraphic displacement (De Beer, 2003). It is thought that these geological features may provide preferential flow paths for groundwater and that recharge may reach the groundwater systems through them from the high mountains (Nel, 2009). The sediments in the Graafwater palaeovalley consists of very fine to coarse sand, silts and clays of the Elandsfontyn, Varswater and Sandveld Formations (Jolly, 1992).

The Atlantis aquifers and the Cape Flats aquifer consists of similar Cenozoic deposits as the Sandveld aquifers and the Lower Berg River Valley aquifer system (Bredenkamp and Vandoolaeghe, 1982; Bertram, et al., 1983; Vandoolaeghe, 1989). At least two palaeochannels can be found in the Cape Flats Aquifer area, with the basement geology being Malmesbury metasediments. (Vandoolaeghe, 1989). It would seem that the Atlantis and Cape Flats aquifers are less complex than the Lower Berg River Valley aquifer system.

The Barcelona Convention identified the loss of groundwater dependent coastal ecosystems as a result of contamination, salinization and the over-exploitation of coastal aquifers as one of the major transboundary environmental concerns. Seepage from coastal aquifers were estimated to contribute approximately a quarter of the freshwater inflow into the Mediterranean. Over-abstraction led to the dying off of coastal ecosystems as well as reduced the volume of freshwater that flows into the sea. In addition, pollutants from agriculture and industry caused the degradation of wetlands, affected the water quality of the seawater and contributed to the decline of fisheries (UNEP-MAP, UNESCO-IHP, 2015). Other countries around the world has increasingly become aware of the importance of coastal aquifers and has put measures in place to protect them and to management them more sustainably.

2.2 Groundwater management

Enslin (1964) penned the following words with regards to water resources and groundwater in particular:

The natural resources of a country determine to a large extent the activities of its population. A shortage of any particular resource, especially water, without which no man or beast can survive, will ultimately set a limit to the general development of that country.

A resource will be of maximum benefit or service only if it is conserved and used as efficiently as possible.

It is therefore essential that the available ground-water supplies of the Republic be determined in order that the future water usage may be planned efficiently for the benefit of the whole nation.

This part will look at the legislative frameworks internationally and in a South African context that guide the governance and management of groundwater.

2.2.1 Legislative Framework

The legislative framework provides the skeleton around which groundwater management strategies should be built. It also falls firmly into the realm of groundwater governance as described by Fourie (2019). The Global Water Partnership (2003; Bucknall, 2006) defines water governance as “the range of political, social, economic and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society”. Water resource governance rests on two core values, namely inclusiveness which ensures that all members receive equal treatment and accountability where authorities have to answer to the people they serve when things go wrong. Things included in water resource management and governance processes are water storage, types of water use, regulations regarding abstraction from a groundwater resource, regulation with regards to discharges, and the allocation of water resources between competing uses. This last item includes allocations to maintain basic environmental services (Bucknall, 2006).

The effective management of water resources is crucial to sustainable development and depends on the following factors (Bucknall, 2006):

- strong policy, legal, and regulatory frameworks;
- more effective implementing organizations;
- a civic determination to improve water governance; and
- appropriate investments.

2.2.2 International best practice

The Rio Declaration and the subsequent Kyoto Agreement contains principles that has been accepted as international best practice. Additional principles are contained in the OECD principles of good water governance.

2.2.2.1 Polluter pays principle

The term was apparently first coined by Lindhqvist (2000; Tojo, 2004), even though the concept may have been around for much longer. The principle entails that those who are responsible for causing pollution to the environment should bear the cost of managing it to prevent damage to human health or the environment. It became part of a set of broader principles to guide sustainable development as set out in the 1992 Rio Declaration (UNESCO, 1992): “National authorities should endeavor to promote the internalization of environmental costs and the use of

economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment.”

2.2.2.2 Precautionary principle

The Rio Declaration (UNESCO, 1992) encapsulates the precautionary principle in the following words: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." A 1998 consensus statement on the meaning of the precautionary principle (Raffensperger and Tichner, 1999; Kriebel, et al., 2001) reads that “when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically.” The precautionary principle is made up of four central components (Kriebel, et al., 2001):

- (i) Taking preventative action in the face of uncertainty;
- (ii) Shifting the burden of proof to the proponent of the activity;
- (iii) Exploring alternatives to possibly harmful actions; and
- (iv) Increasing public participation in decision-making.

Sustainability, sustainable development and Agenda 2030

Sustainability and sustainable development have been the subject of numerous publications and discussions for more than 30 years. It has been set out in a new format in the principles of Agenda 2030, as the Sustainable Development Goals.

Sustainability is defined as “the ability to be maintained at a certain rate or level”, it is also the “avoidance of the depletion of natural resources in order to maintain an ecological balance” (Oxford online dictionary, 2019). The University of Alberta (2012) defined it as “the process of living within the limits of available physical, natural and social resources in ways that allows the living system in which humans are embedded to thrive in perpetuity.” Sustainability is seen as a holistic approach that considers ecological, social and economic facets, with these three components forming the pillars of sustainability (UNESCO, 1992; University of Alberta, 2012).

Sustainable development as the ability to meet “our own needs without compromising the ability of future generations to meet their own needs.” (UNESCO, 1992).

2.2.2.3 OECD principles of good water governance

The OECD Principles of Good Water Governance provides guidelines for the development of policies in each of its member states for improved governance of water resources and to ensure that water governance systems perform optimally (Table 1). It makes it clear that coping with the challenges associated with the governance of water resources would require robust public policies, measurable objectives in pre-determined time-schedules at an appropriate scale and that it should be subject to regular monitoring and evaluation. The principles are intended to contribute to tangible, outcome oriented public policies that are based on three mutually reinforcing and

complementary dimensions of water governance, i.e., effectiveness, efficiency, and trust and engagement (OECD, 2015).

Table 1: The situation in South Africa compared to the OECD principles.

OECD Good Water Management Principle	How do this principle apply to the situation in South Africa?
Enhancing the effectiveness of water governance	
<p>Principle 1. Clearly allocate and distinguish <i>roles and responsibilities</i> for water policymaking, policy implementation, operational management and regulation, and foster co-ordination across these responsible authorities</p>	<p>The roles and responsibilities had been set out in the National Water Act of 1998 (Act 36 of 1998) and the Water Services Act (Act 108 of 1997). There are, however, some roles and responsibilities that still need to be clarified when it comes to groundwater management between the National Department of Water and Sanitation, the Catchment Management Agencies, the Municipalities and the Water Users Associations. Additionally, most Catchment Management Agencies had not been established and the establishment of Water Users Associations to manage water resources on a local catchment scale has been placed on hold.</p> <p>Policymaking is mostly done on a national scale by the Department of Water and Sanitation in the form of Acts, amendment to Acts, Water Resources Strategies, etc. At Municipal level, bylaws are used in connection with delegated responsibilities.</p> <p>Policy implementation would mainly be the responsibility of Catchment Management Agencies, Municipalities and Water Users Associations. Tariff structures are often set by the DWS, to be implemented by the local authorities.</p> <p>Operational management is mainly the responsibility of municipalities and Water Users Associations. Financial models are not functional, as revenue collected for water services are not used in operation, maintenance and improvement of water related infrastructure.</p> <p>Regulations are mainly with the National Department of Water and Sanitation, but a level of regulations are taking place at municipal level in terms of the bylaws.</p> <p>Co-ordination between the different responsible authorities are often very fragmented, and the situation becomes worse where different political parties are in charge, i.e. one party is in charge of the National Department while the official opposition party is responsible for the Provincial and the Local government.</p>
<p>Principle 2. Manage water at the <i>appropriate scale(s)</i> within integrated basin governance systems to reflect local conditions, and foster co-ordination between the different scales.</p>	<p>South Africa has been divided into Quaternary Drainage areas, based on surface water catchments. Groundwater does not follow the same pattern and often transcends the surface water boundaries. This creates problems in the management of groundwater resources. The quaternary drainage areas may be an appropriate scale for surface water, but it does not fit with groundwater systems.</p> <p>The NWA, the NWRS2 and associated strategies were written to respond to long-term environmental, economic and social objectives to make the best use of the available water resources. It is the implementation of the principles set out in the policy documents that is lacking. Risk assessments are often not done, or ignored,</p>

	<p>which means that management is done in a reactionary fashion, instead of planning for the future with timely interventions. Integrated water resources management is a theoretical concept, but the implementation is lacking.</p> <p>Sound hydrological cycle management often falls prey to political goals and interference. The full hydrological cycle is poorly managed, with groundwater being misunderstood and wastewater not seen as a possible resource in most cases. Mismanagement at municipal level often see wastewater treatment works in disrepair with raw sewerage returning to rivers or running down streets as a result of burst pipelines.</p> <p>Adaptive and mitigation strategies are not promoted as management are often political appointments with no understanding of science. The delays in the formation of Catchment Management Agencies means that effective basin management plans were not formulated. Different levels of government and the various government departments too often work in silos, all with their own agendas, that are contradictory. In an ideal situation the department for mining would not promote mining in ecologically sensitive areas or that is of great importance for water resources.</p>
<p>Principle 3. Encourage policy coherence through effective cross-sectoral co-ordination, especially between policies for water and the environment, health, energy, agriculture, industry, spatial planning and land use</p>	<p>Policy coherence is a problem when each government are pushing their own agenda. Cooperative governance is not common between different government departments and different levels of government. The different government departments tend to work in silos. During the drought there was examples of a provincial government, e.g., the Department of Local Governance, Department of Public Works and the Department of Environment and Development Planning, stepping in to appoint groundwater specialists and funding for the development of groundwater resources. There is not competency according to the NWA for the development or management of water resources. DWS did not provide the support that should have been available.</p>
<p>Principle 4. Adapt the level of capacity of responsible authorities to the complexity of water challenges to be met, and to the set of competencies required to carry out their duties</p>	<p>Capacity gaps does not always mean that there are not enough people to do the work, but often that management does not understand what needs to be done. This leads to the hampering of progress by frustrating willing officials with unnecessary red tape, long procurement procedures and lack of funding. The lack of capacity on the form of properly qualified people being appointed in the relevant positions is, however, a real problem in most cases. Often the need for a specific position is not seen as relevant, which means the positions are not created or gets cut due to financial constraints.</p>
<p>Enhancing the efficiency of water governance</p>	
<p>Principle 5. Produce, update, and share timely, consistent, comparable and policy-relevant water and water-related data and information, and use it to guide, assess and improve water policy</p>	<p>A number of data bases have been developed by the Department of Water and Sanitation to provide water and water-related data. This would include the NGA, which provides groundwater information and NIWIS, which contains water related information. These two data bases are web-based and are available to the public. The other data bases used by DWS is not available to the public but will be shared on request. This includes Hydstra (water levels of both surface water flow measured at weirs and other gauging stations and</p>

	<p>groundwater level; other monitoring data may also be included); WMS (water quality data).</p> <p>Unfortunately, consultants and other researchers are not obligated to share “their” data. It is done on a voluntary basis.</p> <p>There is no coordinated effort to collect water related data, and no set standards on what the quality of the product should be.</p> <p>Institutional mapping is problematic, as government departments work in silos and this is often replicated in water related institutions and even within DWS.</p>
<p>Principle 6. Ensure that governance arrangements help mobilise water finance and allocate <i>financial resources</i> in an efficient, transparent and timely manner</p>	<p>Finances for the management of water resources comes from the fiscus (National Treasury), and thus from the taxpayer. The CMAs or in their absence, the Department of Institutional Establishment, is the only part of the water management structure at national level, that collect revenue for water used. Corruption has created problems as well.</p> <p>Municipalities, as the water service provider also collects revenue from their water users that make use of their services, but these funds are not ring-fenced. It often ends up paying for maintenance of roads, the new clinic, or various other needs in the municipality.</p> <p>There is a project called the Waste Discharge Charge System, that holds water users responsible for the effluent that is released into the water cycle, but it is not operational yet.</p>
<p>Principle 7. Ensure that sound water management regulatory frameworks are effectively implemented and enforced in pursuit of the public interest</p>	<p>The NWA has provided ample tools for the management and enforcement, but it seems to lack teeth, so to speak. There is a lack of capacity in the enforcement section (called the “Blue Scorpions”), but there is not punishment such as fines linked to the offences. The only recourse of DWS is to take the offender to court, which is not the best course of action to take for a minor offence.</p> <p>Municipalities have the possibility of fines for offences under their by-laws, but groundwater falls outside their jurisdiction, as it is a nation competency. This created problems during the recent drought in the Western Cape.</p>
<p>Principle 8. Promote the adoption and implementation of <i>innovative water governance practices</i> across responsible authorities, levels of government and relevant stakeholders</p>	<p>DWS contributes to research through the WRC, which promotes water related research. Other than this, the scientific community finds itself outside management and governance of water resources. Application of the legal framework is often rigid with no possibility of experimenting to see what will work best. Part of the problem is in lack of capacity that is competent enough to understand the intention of the law as well as scientific understanding. High staff turn-over adds to the problem. It often becomes a case of the scientists against the government, instead of complementing it, so that both can grow together.</p>
<p>Enhancing trust and engagement in water governance</p>	
<p>Principle 9. Mainstream integrity and transparency practices across water policies, water institutions and water governance frameworks for greater</p>	<p>Batho Pele principles are the code of conduct for officials in DWS, which prescribes the tenets of service delivery. Procedures have been put in place to ensure that decision-makers and stakeholders are held accountable, but they rarely are used. Cadre deployment has created huge problems. There is no unity that could work together for the greater good.</p>

accountability and trust in decision-making	
Principle 10. Promote stakeholder engagement for informed and outcome-oriented contributions to water policy design and implementation	Some stakeholder engagement does take place, but it is usually to inform rather than to get input into a project of buy-in and ownership of a project. It often involves stakeholders that do not quite have the competency to really contribute to the discussion, or to convince stakeholders to agree to the proposal. It thus often becomes a window dressing exercise to be able to tick the boxes.
Principle 11. Encourage water governance frameworks that help manage trade-offs across water users, rural and urban areas, and generations	Trade-offs is not yet a reality as water use authorizations is linked to land ownership or lease agreements.
Principle 12. Promote regular monitoring and evaluation of water policy and governance where appropriate, share the results with the public and make adjustments when needed	Monitoring is mostly done by DWS, but it is not representative of the whole area. It is usually project based or linked to pollution incidents or wellfields. Monitoring requirements have become conditions in water use licences. Data is to be shared with DWS, but water users are not required to share it with the public. Larger water users, like municipalities, are given the requirements of monitoring committees that would include selected stakeholders, to help in managing the resource and its potential impact on the environment.

2.2.3 International legislation

There is a need to protect water resources through legislation around the world. The way in which the challenge is addressed varies from country to country, but the overall aim is the same. Two examples are presented below.

2.2.3.1 European Union

Water Framework Directive (Directive 2000/560/EC of the European Parliament and of the Council of 23 October 2000)

The Water Framework Directive aims for the sustainable use of water. This is achieved through the long-term protection of water resources, reducing the discharge of hazardous substances to surface and groundwater, as well as the mitigation of floods and droughts and their effects (Green, et al., 2013). It is summarized in Article 1 which states the purpose of the directive (European Parliament, 2000):

The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater which:

- (a) prevents further deterioration and protects and enhances the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems;
- (b) promotes sustainable water use based on a long-term protection of available water resources;

(c) aims at enhanced protection and improvement of the aquatic environment, inter alia, through specific measures for the progressive reduction of discharges, emissions and losses of priority substances and the cessation or phasing-out of discharges, emissions and losses of the priority hazardous substances;

(d) ensures the progressive reduction of pollution of groundwater and prevents its further pollution, and

(e) contributes to mitigating the effects of floods and droughts

and thereby contributes to:

— the provision of the sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use,

— a significant reduction in pollution of groundwater,

— the protection of territorial and marine waters, and

— achieving the objectives of relevant international agreements, including those which aim to prevent and eliminate pollution of the marine environment, by Community action under Article 16(3) to cease or phase out discharges, emissions and losses of priority hazardous substances, with the ultimate aim of achieving concentrations in the marine environment near background values for naturally occurring substances and close to zero for man-made synthetic substances

The Water Framework Directive was developed out of need to protect the water resources from deterioration and to ensure good quality water for all its water users. It included surface water, groundwater, marine water and its associated ecosystems. In short, it is meant to protect the water quality and quantity, promote sustainable use, the control of transboundary water problems, protect aquatic ecosystems, terrestrial ecosystems and wetlands that is directly dependent on them, and safeguard and develop potential water uses. Timelines and benchmarks were set for the management of water resources on a water basin level, with a phased implementation of the programmes. It is possible for extensions to be granted, but it needs to be motivated with appropriate, evident and transparent criteria (European Parliament, 2000). Further directives were developed to contribute to the Water Framework Directive. These include the Stormwater Directive (European Parliament, 2007) and the Groundwater Directive (European Parliament, 2006).

2.2.3.1 Arizona, USA

The USA is a federation of states and as such each state is responsible for their own legislation. The Groundwater Management Act was published in 1980 as a result of rapid groundwater level declines in the 1960s and 1970s (Paul, 2018). Groundwater has special protection in five geographical areas, known as Active Management Areas (AMAs). These areas are similar to the Subterranean Government Water Control Areas in South Africa under the Water Act of 1956 (Act

54 of 1956). The five AMAs are Prescott, Phoenix, Pinal, Tucson and Santa Cruz. Paul (2018) lists ten aspects to take note of when considering the Groundwater Management Act of Arizona:

1. Most of the water used in Arizona comes from groundwater (41%), with 38% from the Colorado River, 18% from other in-state rivers (especially the Salt and Verde) and 3% from high-quality treated wastewater.
2. More than 75% of the population in Arizona lives within the AMAs.
3. The Groundwater Management Act (1980) mandated the conservation of groundwater by all sectors.
4. There are few restrictions on groundwater use outside the AMAs, with the result that consumer protection is weak and significant problems such as declining water levels and the risk of communities running out of water are emerging.
5. Provision has been made for counties and municipalities outside the AMAs to voluntarily sign up for stricter groundwater protection. Counties such as Cochise and Yuma and the towns of Clarkdale and Patagonia are examples where stricter groundwater protection is enforced, and new developments have to show that there would be enough water to sustain the population for the next 100 years.
6. Over-abstraction of groundwater can lead to drying up of wells, there will be less water in streams and rivers as a result of reduced baseflow, the water quality will decrease and may cause land subsidence.
7. Rivers, such as the San Pedro and the Verde rely on groundwater to sustain their flows, but the water laws in Arizona does not adequately recognize the hydrologic connection between groundwater and surface water.
8. Efforts has been made recently in the legislative sessions to weaken the Groundwater Management Act, when it needs to be strengthened.
9. Cities within the AMAs need to replace the water that they abstract by Managed Aquifer Recharge, often using the excess water in the Colorado River and thereby earns storage credits for times when the surface water supply is low.
10. Recharge to rivers does not earn similar credits, despite its importance to maintaining a healthy ecosystem. It may be necessary to provide incentives to cities to reinvest into their river systems.

The excessive use of groundwater contributes to the decline of healthy habitats and studies have shown that losses of natural habitat in central Arizona, especially along the Santa Cruz, Gilu and Salt Rivers, are primarily the result of groundwater abstraction. This situation creates an uncertain future to many of the rural and small communities in Arizona, and careful planning would be necessary to protect the groundwater resources (Paul, 2018). Arizona and California went through a very bad drought recently, which highlighted the importance of proper water resource management. Groundwater in these states is still managed separately from surface water to a great extent.

2.2.4 South African Legislation

The South African legislation around water resources compare favourably with that of the rest of the world.

2.2.4.1 National Water Act of 1998 (Act 36 of 1998)

The National Water Act (NWA, 1998) begins with the following preamble as a reason for the enactment of the legislation:

Recognising that water is a scarce and unevenly distributed national resource which occurs in many different forms which are all part of a unitary, interdependent cycle;

Recognising that while water is a natural resource that belongs to all people, the discriminatory laws and practices of the past have prevented equal access to water, and the use of water resources;

Acknowledging the National Government's overall responsibility for and authority over the nation's water resources and their use, including the equitable allocation of water for beneficial use, the redistribution of water, and international water matters;

Recognising that the ultimate aim of water resources management is to achieve the sustainable use of water for the benefit of all users;

Recognising that the protection of the quality of water resources is necessary to ensure sustainability of the nation's water resources in the interest of all water users; and

Recognizing the need for the integrated management of all aspects of water resources and, where appropriate, the delegation of management functions to a regional or catchment level so as to enable everyone to participate;

According to the Act, the management of the water resources, whether surface water or groundwater, as part of the integrated hydrological cycle is the competency and responsibility of the National Department of Water and Sanitation, with the Minister of Water and Sanitation acting as custodian of the water resources. There is no competency for the management of water resources on a provincial or local level, as water resources transcends political boundaries, and should not be used as a tool to ensure certain political outcomes. It is also to ensure that the management of the water resources in the country is to the benefit of all water users, not just those of a specific region. This becomes especially important in the light of the large amount of inter-catchment transfer schemes in the country. The provision of water services is managed on a local level (municipalities, both local and district) under the Water Services Act of 1997 (Act 108 of 1997) and does not include the management of the resource as such. Groundwater management is especially challenging, especially when it comes to its regulation at local level. There is no legal framework for municipalities to include it into their bylaws, other than that of voluntary borehole registration, and a few other requirements pertaining to groundwater and its management.

The challenge regarding groundwater management is increased in the fact that groundwater and surface water to a great extent is still managed as two different resources, that groundwater was seen as private property under the Water Act of 1956 (Act 54 of 1956) and the fact that the concepts and language used in the NWA to explain the management and regulation of groundwater is that of surface water and not that of groundwater. In addition to that, groundwater does not conform to surface water boundaries. Groundwater unit are often larger as the quaternary drainage areas that has been delineated as management units.

2.2.4.2 Water Act of 1956 (Act 54 of 1956)

Groundwater was considered as private property under the Water Act of 1956 (Act 54 of 1956), and it was only in terms of Chapter 3 of the act that government could protect groundwater. One of the ways in which this could be done, was through the declaration of Subterranean Government Water Control Areas. The promulgation was usually associated with dolomitic aquifers and artesian aquifers.

Subterranean Government Water Control Areas / Groundwater Control Areas

Groundwater had not been regulated in the Water Act or 1956 (Act 54 of 1956), except for Chapter 3 that describes Groundwater Control areas or Subterrean Government Water Control areas. The purpose of Subterranean Government Water Control Areas (SGWCAs) was to protect vulnerable, major aquifers, mostly those found in dolomitic systems (karst aquifers) and other artesian aquifers. Artesian aquifers can be found in almost any geological system – primary aquifers consisting of gravel and sand, or hard rock, fractured aquifers. It is especially the dolomitic systems and the porous, primary aquifers that are vulnerable to pollution and susceptible to degradation by human activities that needed the special protection that this part of the Water Act (Act 54 of 1956) addressed.

Subterranean Government Water Control Areas / Groundwater Control Areas in the Western Cape

The first groundwater control area in the Western Cape – the Saldanha Subterranean Government Water Control Area - was declared because drilling during exploration work found strong artesian wells with good quality groundwater. Decision makers at the time realized that it could be an additional source of water to supply the ever-expanding City of Cape Town with water, especially since the city had experienced a number of water scarce periods. The groundwater control areas were declared in areas where there was limited or no surface water supply for the towns and communities that settled in the area. In most cases through exploration good quality groundwater was found, with a relatively good yield in the areas that was declared groundwater control areas. One of the exceptions is the Strandfontein Subterranean Government Water Control area, where the water quality is not as good. Figure 6 shows the Subterranean Government Water Control Areas in the southern part of the Western Cape.

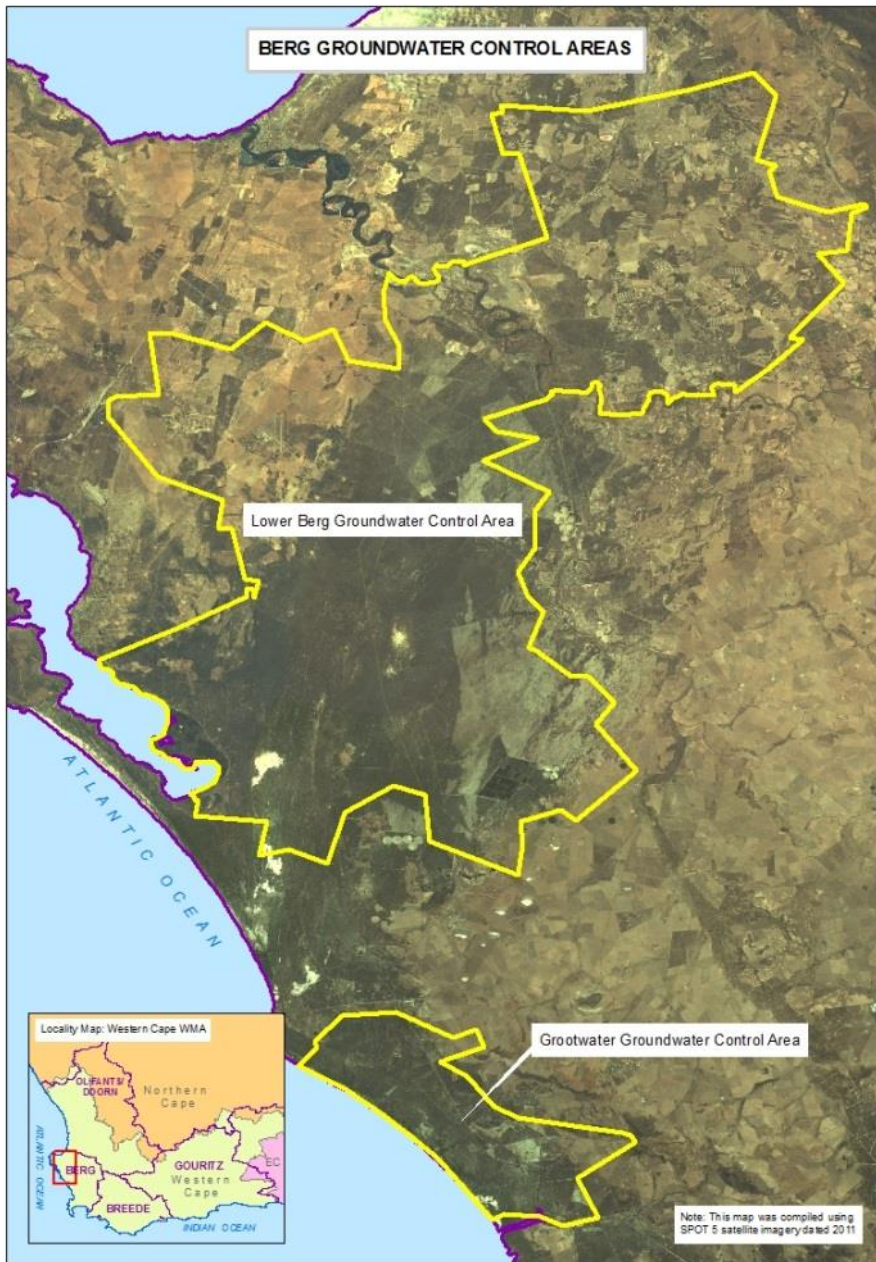


Figure 6: Map showing the Subterranean Government Water Control Areas in the Berg River catchment area.

The ***Saldanha Subterranean Government Water Control Area*** was the first such area in the Western Cape (RSA, 1976). Exploration work in the late 1970s till early 1990s led to the expansion of the Saldanha Subterranean Government Water Control Area in 1990. It was known as the ***Lower Berg River Valley Subterranean Government Water Control Area***, which included the Adamboerskraal, Langebaan Road and Elandsfontein Aquifer units. No formal proclamation could be found to date for the Lower Berg River Valley Subterranean Government Water Control Area, but documents around the General Authorizations (RSA, 1999) for both the Lower Berg River

Valley and Saldanha areas give reference to Notice 185 of Government Gazette 5282 dated 10 September 1976. This expanded area is also indicated on maps and in other documents and reports as if the proclamation was made. The **Yzerfontein Subterranean Government Water Control Area** – covering the Grootwater Aquifer unit - was declared in 1990 (RSA, 1990a) with allocations following in 1992 (RSA, 1992).

The **Strandfontein Subterranean Government Water Control Area** (RSA, 1988), **Wadrif Subterranean Government Water Control Area** (RSA, 1990b) and **Graaffwater Subterranean Government Water Control Area** (RSA, 1990c) in the Olifants River Catchment came into being around the same time as the Yzerfontein Subterranean Government Water Control Area. This area falls outside the study area.

Specific regulations with regards to Subterranean Government Water Control Areas (RSA, 1981). It replaced an earlier notice (RSA, 1963). The Annexure of the 1981 proclamation was incorrect and was later replaced (RSA, 1986). Bekker (1989) compiled a report of all the Subterranean Government Water Control Areas in the country, that was very comprehensive.

2.2.4.3 Other Acts and Strategies linked to groundwater management

The **National Water Resources Strategy 2** (NWRS2) and the earlier version of the document provides information on the implementation of the NWA.

Strategies that have a direct link with groundwater management is the **Dolomite Strategy**, the **Artificial Recharge Strategy** and the **National Groundwater Strategy**.

The **Water Services Act of 1997 (Act 108 of 1997)** has to do with the water service providers that supply water to municipalities (RSA, 1997). In some cases, there is a separate entity, such as BloemWater or RandWater, but this function is in most cases fulfilled by the municipalities themselves.

There is other legislation that has an indirect bearing on the management of water resources.

Instruments provided by the NWA for the management of groundwater resources

Some of the tools available for the management of water resources, is described in Chapter 3 of the NWA. This includes the **Water Resource Class** (Section 13) and the **Resource Quality Objectives** (Section 14). These tools are setting the benchmark or standards against which water resources are to be managed. The **Reserve** (Section 16) consists of two components, i.e., basic human need and environmental need. It is meant to ensure that the resource is never depleted, as it holds the necessity in trust.

Water use authorisations can also be used as a way to manage or protect water resources. There are different kind of water uses. Section 22 list the permissible uses that does not require a water use licence. The first is **Schedule 1** use, which is the water needed for reasonable domestic use, watering of the garden, and stock watering. As soon as there is a commercial aspect linked to the water use, it is no longer a Schedule 1 use. The second use is **Existing Lawful Use** meant that the water use was lawful during a window period between 1996 and 1998. Conditions around existing

lawful use are described in Sections 32 to 35. The third permissible water use is the **General Authorisation**, as described under Section 39. This water use is deemed to have a low enough impact that it does not have to go through the whole authorisation process. There are some conditions linked to this water use authorisation, but it cannot be adjusted with site specific details and requirements. Water users that do not meet the requirements of the authorisations above as a result of the volume needed or the severity of the impact of the proposed activity, has to go through the whole authorisations process in order to obtain a **water use licence**. The requirements of the application procedure and other conditions connected to the water use licence is contained in Sections 40 to 42. **Compulsory Licensing** (Section 43) is the final option if the water use exceeds the available supply. The process of compulsory licensing entails a redistribution of the available supply, which may mean the reduction in the volume that an individual water user may abstract in order to allocate water equitably to other water users. It is possible to manage the water resource through the conditions set in individual water use licences. Some of the general conditions can be found in Sections 49 to 52. Site and case specific **conditions of authorisation** can be set by the case officer working on the licence application and the specialist scientists that provided comments on the licence.

2.2.4.4 Questions of scale and measurements

The NWA is a well-structured document. It was written by forward thinking men and women. It tried to include everything that was known about sustainable development, integrated water resource management principles and the science connected to water resources. It included groundwater in much more than just one chapter, with the understanding the groundwater is an integrated part of the water cycle and that it is inextricably linked to the surface water. Groundwater made up a greater part of the legislation than the one chapter (Chapter 3) that was dedicated to the subject in the Water Act of 1956.

When working extensively with the NWA and the implementation thereof in connection with groundwater and its authorisation, its failings and problems become apparent. The drought in the Western Cape just made some of it glaringly obvious, as had the recent development of Water Resource Classes and Resource Quality Objectives for the Berg Area of the Berg-Olifants Catchment. The biggest failing of the NWA is the fact that it is based on surface water boundaries and characteristics. This will be illustrated in the section below (initial discussion in Vermaak, et al., 2019b).

(i) *Resource Assessment*

Surface water catchments vs groundwater units

South Africa has been divided into catchment areas based on surface water boundaries, with topography playing an important role when deciding where the boundary should be. The river catchments were then divided into smaller units with the smallest being the quaternary drainage area or catchment. In theory this should be the most correct way of doing it so that you end up with water resource units that are manageable. One of the basic principles that are widely used in groundwater – that a topographical high indicates a groundwater divide – means that groundwater

should, in theory, follow the same patterns as surface water. The reality shows that this is not the case, as illustrated in Vermaak and De Haast (2012). The extent of aquifers does not always coincide with that of the surface water catchments or quaternary drainage areas. This is shown in Figure 7, where the estimated extent of the Lower Berg River Aquifer System can be seen crossing a number of the surface water boundaries. It forms part of 5 different quaternary drainage areas, namely G10K, G10L, G10M, G21A and G30A. One of the reasons for this is that geology is often more important in creating groundwater units or systems than topography (Vermaak and De Haast (2012)).

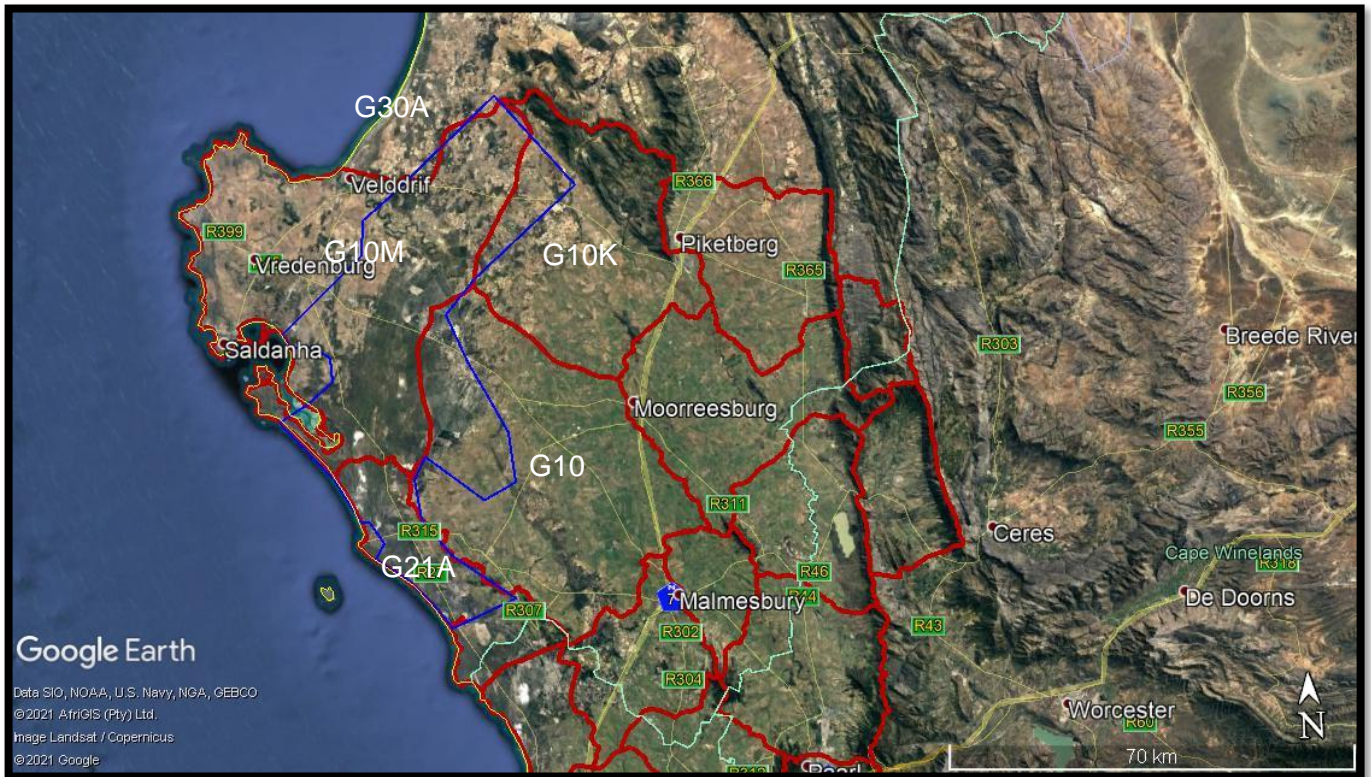


Figure 7: Satellite image showing quaternary drainage areas for the Berg River area (red polygons) and the estimated extent of the Lower Berg River Aquifer System (blue polygon) (Vermaak, et al., 2019b).

- Reserve

The idea behind the Reserve is to ensure that there will always be water available for basic human needs and the ecology. It is often illustrated with a container (Figure 8, left hand illustration) where a percentage of the water in the bottom is reserved for basic human needs and the environment. The rest would thus be available for allocation to water users. When taken at face value the Reserve is a brilliant concept, but not practical to implement in groundwater. This is especially true when implemented according to quaternary drainage area.

Groundwater cannot be made to fit into this mould, as it occurs below ground and it is thus the part that overflows that feeds into the baseflow of rivers and which is available for the use of the environment. The exception is during times of groundwater flooding as often happens on the Cape Flats during winter. If the environmental allocation from groundwater is the upper part of the

container (Figure 8, right hand illustration), it raised the question of whether there is any groundwater that is available for allocation to groundwater users. A second question that comes as a result of the first is whether the reserve is the best way to ensure that groundwater would always be available for basic human needs and the ecology. During a lecture to the students at IGS, Van Tonder (2010) discussed the concept of the Reserve and gave an alternative way of ensuring the sustainability of the groundwater resource. The outcome of the discussion was that the abstraction of one person should not go below the level of the main water strike in a fractured setting, neither should it negatively impact his neighbour nor the baseflow to a river or discharge to a wetland. The practical application of this still needs to be determined.



Figure 8: Illustration to show the difference between the conventional understanding of the reserve with the situation for groundwater (Vermaak, et al., 2019b).

Additional problems with the Reserve are in the application of the concept. One example comes from a report done for the Water Use Licence application that was done for a client that is located in quaternary drainage area G10L (Figure 9). It is necessary to give a brief overview of the geology in the catchment to understand the example. The Darling Granite Pluton can be found along the southwestern border of the area, with Malmesbury shale being close to the surface just north of Malmesbury in the south, and along the northeastern border of the catchment near Moorreesburg and Hopefield. The rest of the catchment is covered with Cenozoic sediments that forms part of the Lower Berg River Aquifer System.

The client and their details were not important; it was the methodology that was used that is. The basic argument was that the surface area of the land owned by the client is for example 10% of the surface of the catchment. The client is therefore entitled to 10% of the volume of water that was available in the catchment. The geohydrological characteristics of the geological units in this quaternary drainage area is variable within itself and differs greatly between the different geological formations. This may lead to unrealistic expectations, especially where the geological conditions are not conducive to aquifer development.

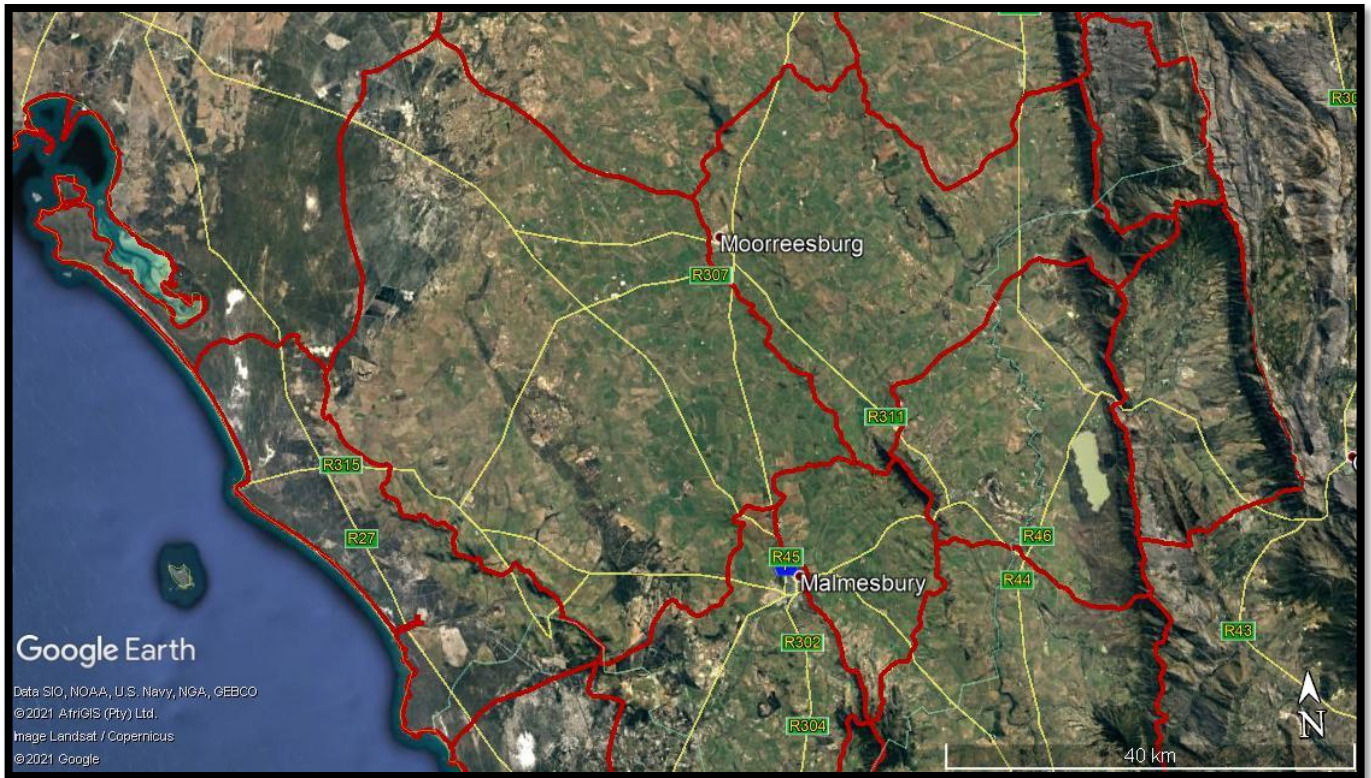


Figure 9: Satellite image showing the quaternary drainage areas for part of the Berg Area (Vermaak, et al., 2019b).

This brings us to the next example that is currently creating problems to people applying for water use licences in the Western Cape. Officials of DWS are using the Reserve Determination to decline Water Use Licence applications, stating that there is not more water available for allocation for the quaternary catchment according to the Reserve calculations. As mentioned above, the Cape Flats Aquifer is spanning three quaternary drainage areas, i.e., G22C, G22D and G22E (See Figure 10). The recharge for the aquifer comes from a limited volume of local, direct recharge. The rest of the recharge comes from the slopes of Table Mountain on the western side of G22C and G22D, from the Durbanville Hills in the north of G22C, Tygerberg in the middle of the three quaternary drainage areas, as well as the Hottentots-Holland mountains to the east of the basin.

The Reserve cannot be a set number and should not be linked to surface water boundaries. In its current format it is based on information available for the shallower aquifers, as these aquifers are the contributing to base flow, which forms the environmental part of the reserve. A large number of the developments in the Western Cape has targeted the deep aquifers. This means that not a lot is known about them and would therefore invalidate the Reserve that was based on information for shallow aquifer. In additions to this, the Table Mountain aquifer is a massive system that stretches from Graafwater in the Olifants-Doorn area down to Cape Agulhas and then towards the Eastern Cape. It would thus not make sense to use the Reserve for a quaternary drainage area for

shallow aquifers on a massive groundwater system, that is often confined and that is in places more than a kilometer below surface.



Figure 10: Satellite image showing the quaternary drainage areas for the False Bay basin containing the Cape Flats Aquifer (Vermaak, et al., 2019b).

The confidence levels of the Reserve that was done for the Berg Area is very low, as it was only done on Desktop level based on the Groundwater Resources Assessment II (GRAII), which used outdated and limited information and recharge estimations that was based on rainfall values of more than 2 decades ago (See Table 2). Recharge is a factor of rainfall and it also varies with seasons. It is at this stage a very contentious parameter, due to the high level of uncertainty connected to its determination. It is an estimated value, as it cannot be measured. If you change the rainfall, it will theoretically change the recharge, and it would thus affect the volume of water that would be available for allocation. There should then be less water available for allocation during periods of drought. The same can be said of baseflow, which is a calculated value based on a number of assumptions. The uncertainty linked to just these two values will affect the rest of the values and make the calculation highly inaccurate. WARMS data is an additional hurdle in the determination of whether there is water available for allocation as it does not accurately reflect the water that is being used. The Verification and Validation process that was run recently was highly flawed and has not been completed.

Table 2: Application of the Reserve in a licence application (Vermaak, et al., 2019b).

Table 2a: Groundwater Reserve for quaternary G22K								
Catchment	Area (km ²)	Recharge (Mm ³ /a)	Population	Base flow (Mm ³ /a)	EWR_MLF (Mm ³ /a)	BHN Reserve (Mm ³ /a)	EWR as % of Recharge	BHM as % of Recharge
G22K	80.4	7.1	88.425	1.1	5.6	0.81	78.9	11.4

Table 2b: Analysis of Groundwater Reserve for quaternary G22K							
Recharge (Mm ³ /a)	Reserve (Mm ³ /a)	Available Water before Registered Users (Mm ³ /a)	WARMS report on existing users ((Mm ³)		Available Water for allocation (Mm ³ /a)	Applicant Requirements (Mm ³ /a)	Available after allocation (Mm ³ /a)
			Per annum	Monthly			
7.1	6.7	0.4	0.46		-0.06	0.01	-0.07

Despite the fact that the Berg Area is the economic hub of the Western Cape, no further Reserve Determinations at a higher level of assurance has been done. The drought in the Western Cape has also not put it on a list to be fast-tracked because of its importance and the number of Water Use Licence applications that was received in the region. A comprehensive Reserve was done for the Olifants-Doorn part of the Berg-Olifants Catchment, even though it is a very arid area where the volume of groundwater use is not as high as in the Berg Area.

- Water Resource Classes and Resource Quality Objectives

Meant to determine the desired state of the water resource and the ideal quality and quantity it needs to be maintained against.

Quality standards difficult to implement in groundwater, as the quality of the groundwater is dependent on the geology in the area. Not possible to manage quality in situ and dilution not an option, as in surface water. Interesting the groundwater is rejected as possible resource when quality is not within the desired limits for the parameters used, but surface water gets treated, no matter what the quality.

Quantity will depend on rainfall and recharge rates; becomes even more difficult to manage is recharge area is often outside of the drainage area used for the exercise.

- Groundwater Protection Zoning

Protection of groundwater systems against pollution and deterioration is not sufficient. Protection zones can and should be applied at different scales as necessary to protect the aquifer against impacts of human activities (Figure 11). It will also be more important if the aquifer is being used as a source of potable drinking water. There are five zones that can be considered for implementation (DWAf, 1995; DWAf, 2008a; Miljøstyrelsen, 2000; Foster, et al., 2002; Chave, et al., 2006; EA, 2012; Nielsen, 2017; Fourie, 2019). These include:

- Wellhead Operational Zone
- Inner Protection Zone

- Outer Protection Zone
- Source Catchment Protection Zone
- Zones of Special Interest

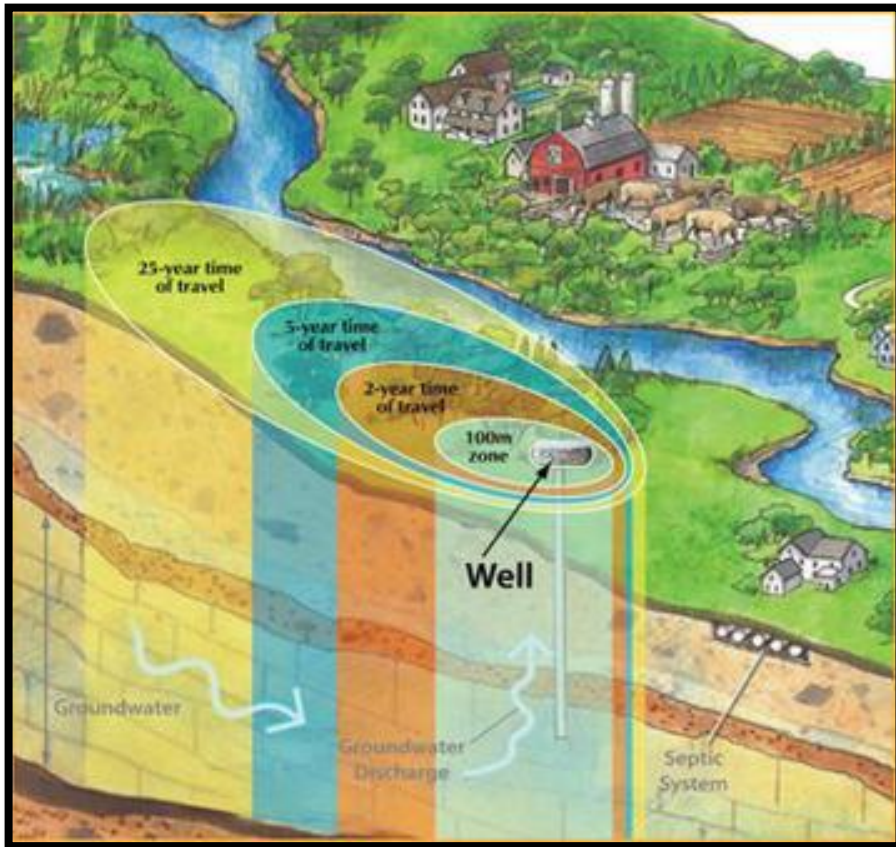


Figure 11: Example of protection zones around a wellfield (Halton-Hamilton, 2010).

(ii) *Groundwater availability*

It is difficult to allocate a resource if one is not sure how much there is. This is the situation with groundwater. In most cases, groundwater availability is an estimate from data that is available. The last comprehensive groundwater resource assessment was the GRAII programme, but it used outdated, inaccurate data, which was estimated on maps using a different map reference system. The availability of groundwater as estimated through the GRAII study is given in

Table 3, while the groundwater availability by NIWIS can be seen in Table 4. The WARMS data has not been updated with the latest information, and no Reserve study has been done for the Berg River catchment area. The Reserve volumes that are available (see Table 2), are based on desktop assessments – i.e. the GRAII data.

Table 3: Groundwater availability for part of the Berg River catchment area, according to GRAII (Vermaak, et al., 2019b).

Quaternary Catchment	Area			Utilisable Groundwater Exploitation Potential [m ³ /a/catchment]	
	m ²	km ²	Ha	Normal UGEP	Dry UGEP (dry)
G10A	171 779 354	172	17 178	28 662 100	22 935 600
G10B	125 973 064	126	12 597	16 783 200	13 214 800
G10C	328 066 330	328	32 807	20 494 200	15 794 700
G10D	687 551 289	688	68 755	15 536 600	10 461 500
G10E	394 096 556	394	39 410	7 059 790	3 280 970
G10F	539 356 648	539	53 936	5 136 390	2 643 200
G10G	185 576 074	186	18 558	13 653 200	10 410 500
G10H	674 523 451	675	67 452	2 835 940	1 323 560
G10J	867 507 282	868	86 751	2 422 470	101 513
G10K	1 175 888 103	1 176	117 589	7 626 970	5 062 690
G10L	1 754 553 670	1 755	175 455	12 515 000	8 289 660
G10M	2 004 220 277	2 004	200 422	14 877 600	9 240 830
G21A	524 338 789	524	52 434	7 759 980	4 977 610
G21B	304 610 692	305	30 461	1 676 290	-140 513
G21C	244 217 078	244	24 422	1 906 000	1 123 770
G21D	484 048 047	484	48 405	3 633 350	1 982 440
G21E	530 763 038	531	53 076	4 833 200	1 870 820
G21F	242 391 740	242	24 239	2 930 290	1 514 010
G22A	238 805 264	239	23 881	6 746 240	4 250 310
G22B	109 185 047	109	10 919	4 378 140	2 970 320
G22C	254 197 151	254	25 420	7 429 930	4 818 980
G22D	247 397 254	247	24 740	11 629 500	7 716 790
G22E	271 602 973	272	27 160	4 145 450	1 902 430

Table 4: Groundwater resource availability for some of the Berg River catchment area according to NIWIS (Vermaak, et al., 2019b).

Quaternary	Reserve Study	Available (GRA2) [m ³ /a]	Recharge (GWR) [m ³ /a]	Reserve (GWR) [m ³ /a]	Abstracted (WARMS) [m ³ /a]	Surplus (GRA2) [m ³ /a]
G10A	FALSE	22 935 600			3 635 508	19 300 092
G10B	FALSE	13 214 800			612 800	12 602 000
G10C	FALSE	15 794 700			5 797 884	9 996 816
G10D	FALSE	10 461 500			3 493 515	6 967 985
G10E	FALSE	3 280 970			5 055 889	-1 774 919
G10F	FALSE	2 643 200			280 473	2 362 727
G10G	FALSE	10 410 500			0	10 410 500
G10H	FALSE	1 323 560			3 041 119	-1 717 559
G10J	FALSE	101 513			279 273	-177 760
G10K	FALSE	5 062 690			7 099 893	-2 037 203
G10L	FALSE	8 289 660			3 084 197	5 205 463
G10M	FALSE	9 240 830			2 573 271	6 667 559
G21A	FALSE	4 977 610			765 260	4 212 350
G21B	FALSE	1 676 290			5 714 760	-4 038 470
G21C	FALSE	1 123 770			1 459 416	-335 646
G21D	FALSE	1 982 440			6 834 054	-4 851 614
G21E	FALSE	1 870 820			3 606 239	-1 735 419
G21F	FALSE	1 514 010			127 700	1 386 310
G22A	FALSE	4 250 310			151 925	4 098 385
G22B	FALSE	2 970 320			526 978	2 443 342
G22C	FALSE	4 818 980			3 049 042	1 769 938
G22D	FALSE	7 716 790			8 391 936	-675 146
G22E	FALSE	1 902 430			1 062 438	839 992

When looking at the groundwater availability compared to the registered water use on the WARMS data base, it provides a scenario that should cause alarm. Figure 12 shows the groundwater availability according to GRAII compared with the registered water use on the WARMS data base per water management area. According to this graph the groundwater that is available in the Berg-Olifants Water Management Area is fully allocated. This leaves no room for growth – economically and for the population. During the drought, people turned to groundwater to ensure their water supply, which means that when their water use is registered on WARMS there will most probably be a deficit.

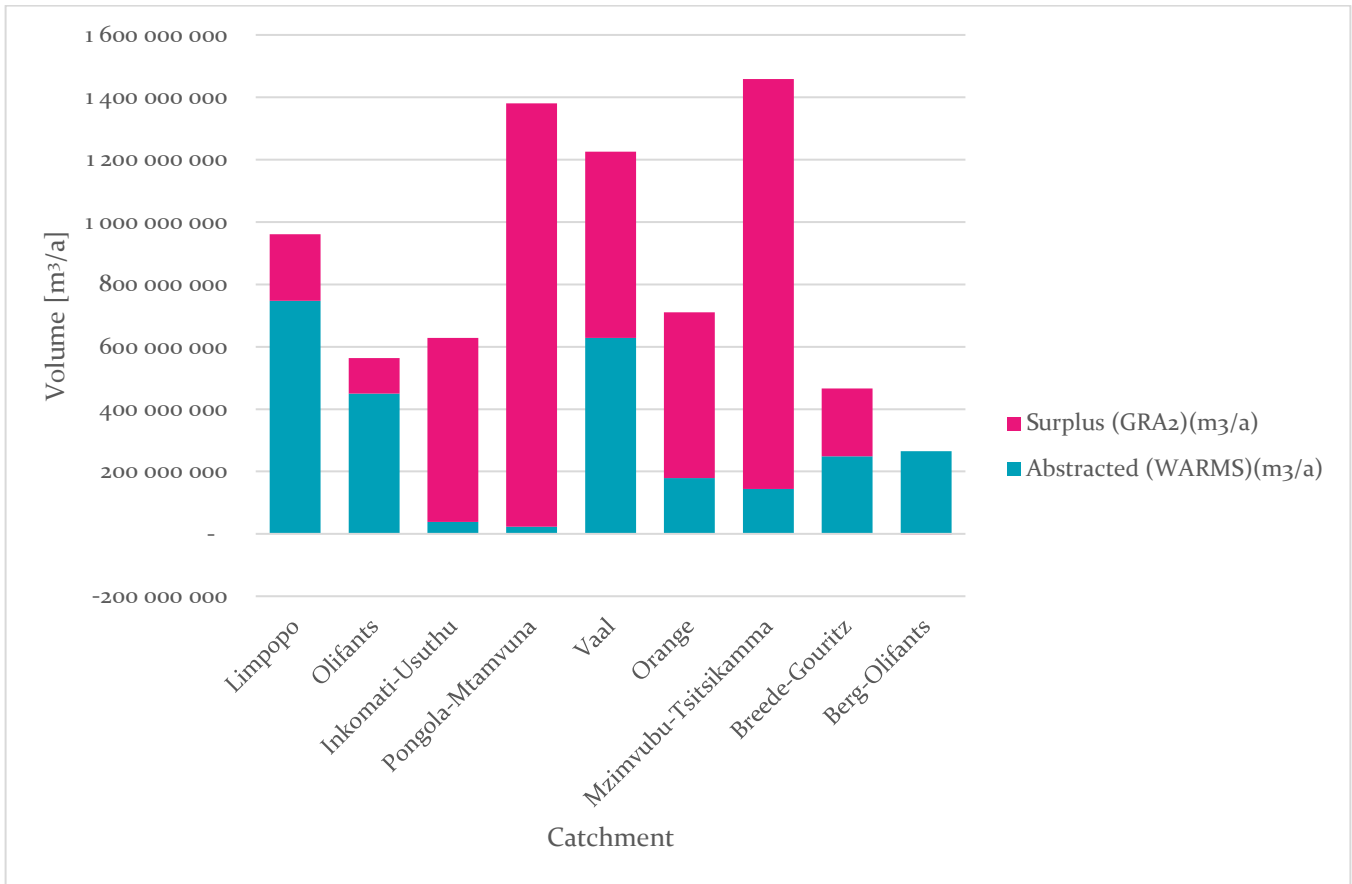


Figure 12: Groundwater availability according to GRAII compared to registered water use on WARMS per water management area (Fourie, 2018; Vermaak, et al., 2019b).

When comparing groundwater availability with registered water use per province, it is Gauteng that makes the warning lights go on (Figure 13). Gauteng is very clearly using more groundwater than what is available in the province. This means that if volumes on both sides (availability and registered water use) is correct, the groundwater use is greater than what is available in some instances. It could only result in damage to the aquifers and the associated ecosystems.

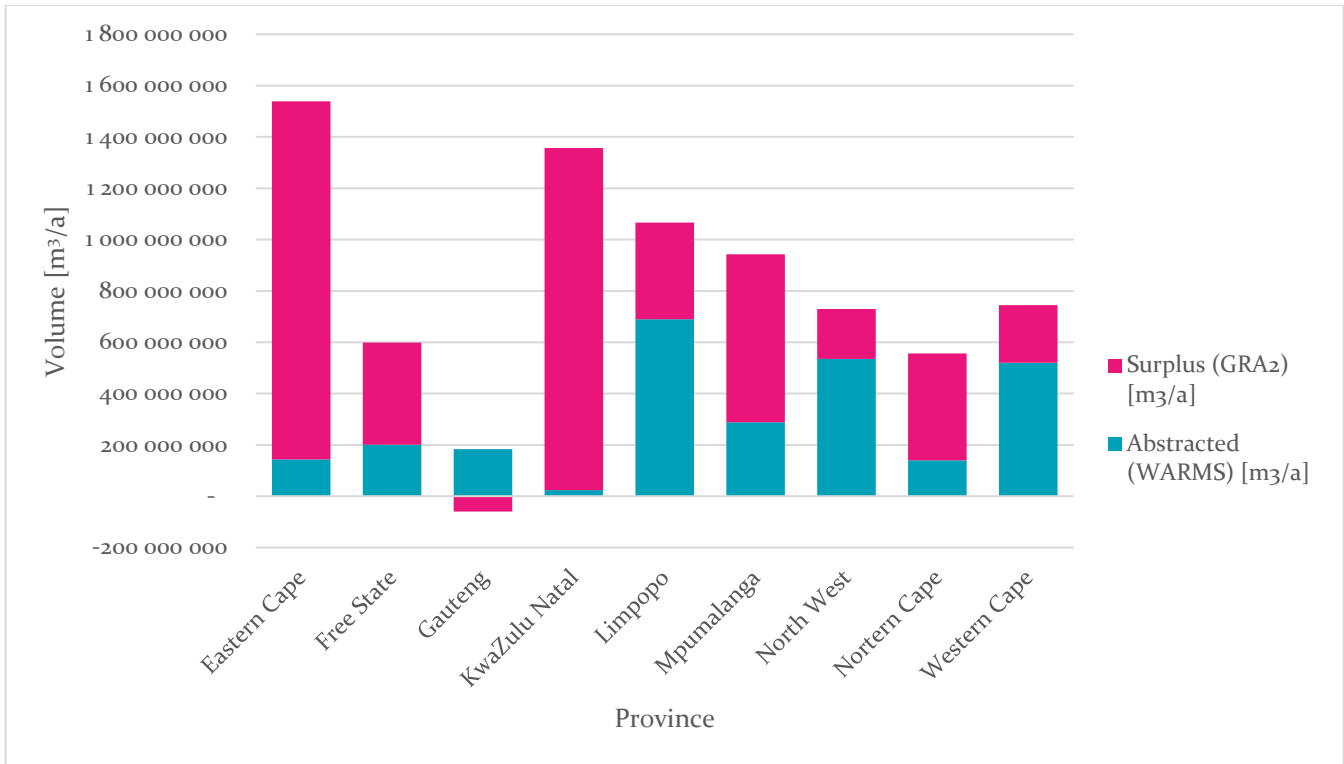


Figure 13: Groundwater availability according to GRAII compared to registered water users on WARMS per province (Fourie, 2018; Vermaak, et al., 2019b).

(iii) Allocation Methodology

There are also challenges with regards to the allocation or authorisation of groundwater resources on top of the problem of not knowing whether there is any water left to allocate to new water users. Water use licence applications are evaluated individually, and there may be a number of applications in the same area. Very seldom are the cumulative effect of these water uses taken into account when the licence is awarded. The compliance side of this also creates problems, as will be demonstrated below.

The different types of authorisation were meant to make the process less cumbersome for the general water users but created its own set of problems. When it comes to the Existing Lawful Use group, there is no control over the impact of the water use, as there were not conditions set or monitoring required. In most cases there are no record of volumes abstracted or water level measurements taken. The compliance section also does not have the capacity to monitoring these water users adequately, and in most cases, officials have to rely on complaints from the general public. One of the examples are shown in Figure 14. BGo0124 is a production borehole for an Existing Lawful User who used to have a pivot point irrigation system for potatoes, which thus would have taken place during the window period to deserve the designation. The abstraction volume in early 2010 was at 12091m³ for the quarter – thus 4030.33m³ on average for the month. It was the highest volume abstracted in the recorded history of the monitoring done for the area. There are 3 other abstraction boreholes on the farm in close proximity. The record of abstraction

began at the turn of the century, which actually means that the abstraction was not recorded during the window period for the use to be considered as Existing Lawful Use (ELU). Abstraction for the quarter ending in June 2015 was 1360894m³, which makes it 453631.33m³ per month on average. It is almost 100 times more than the previous highest recorded reading.

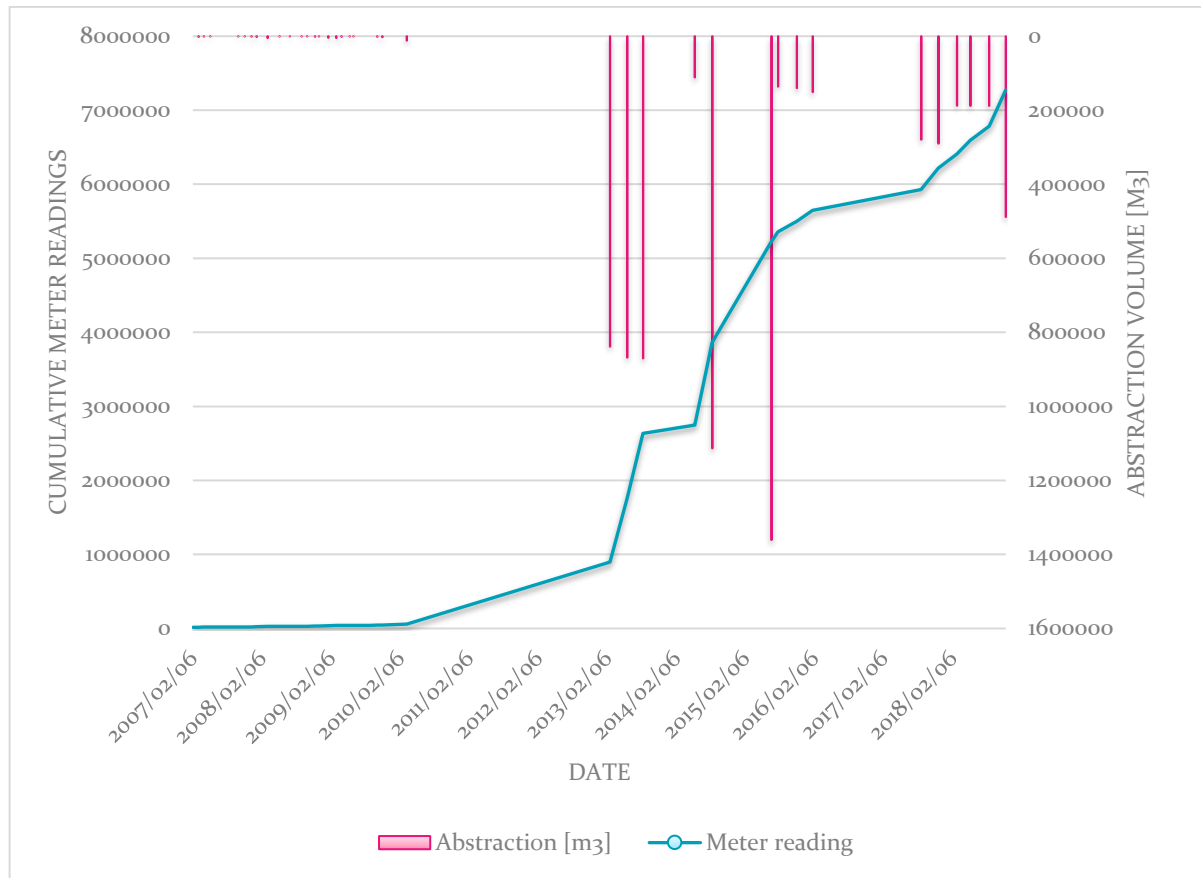


Figure 14: Abstraction volumes and meter readings for BGo0124 in the Hopefield area (Vermaak, et al., 2019b).

When the idea of a Schedule 1 use was developed, the idea of a rural setting must have been the picture that was envisioned. Schedule 1 use at high densities can be more detrimental than a well-managed wellfield for bulk supply. Figure 15 shows the results of a hydrocensus that was done in the Bellville area. All of the data points would be considered Schedule 1 users. There is not control over the volumes that Schedule 1 use entails, as reasonable can be interpreted differently. In addition, almost all Schedule 1 users of groundwater do have a municipal connection, that already supplies them with their Schedule 1 water (reasonable domestic supply and watering of a garden). It would thus seem like double allocations. Groundwater use under Schedule 1 does not need monitoring and no conditions are linked to it – except registering the borehole with the municipality if their bylaws require it. There is thus no control over the volumes abstracted or measurements linked to it. This makes it difficult to quantify the groundwater used by Schedule 1 users. Managing this groundwater use within municipal boundaries also causes jurisdictional headaches, as it is within the municipal boundaries, but the municipalities do not have the

delegated powers to act against unlawful acts linked to groundwater. There is no capacity to monitor these water users or to establish whether they are compliant with the NWA.

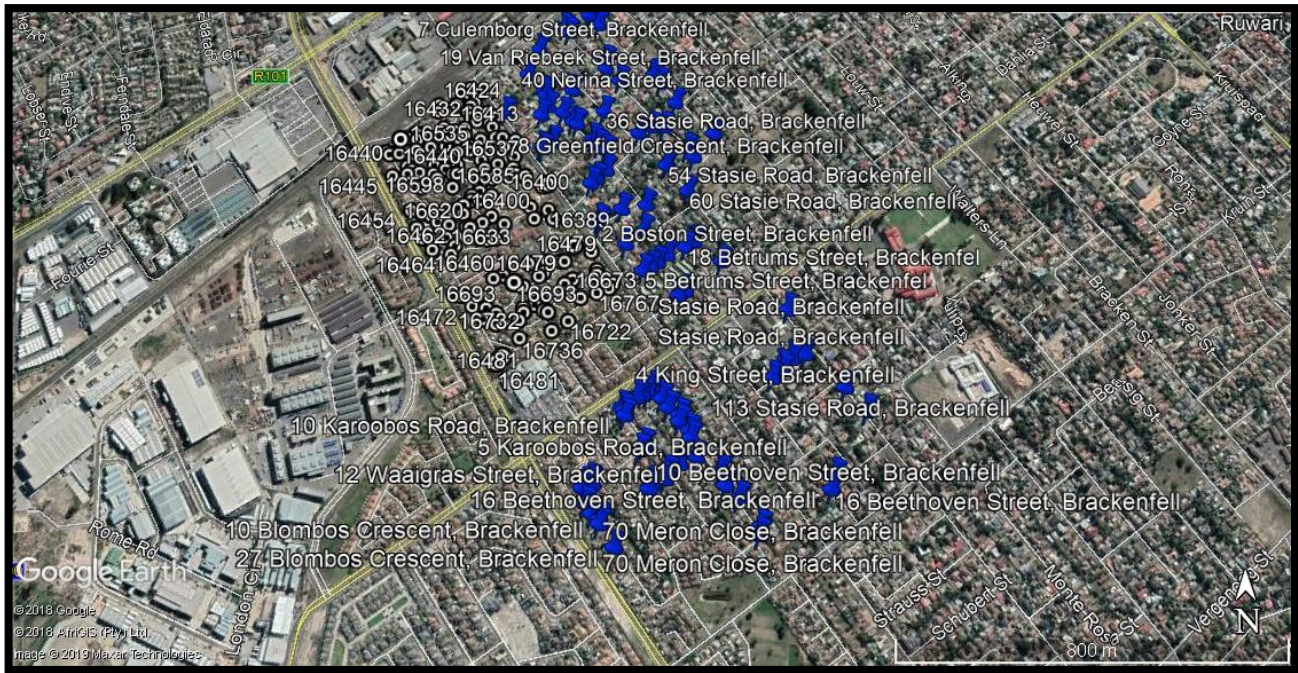


Figure 15: Results of a hydrocensus in Bellville (Vermaak, et al., 2019b).

The General Authorisations for the higher rainfall areas in the mountains is set at higher volumes than in the Lower Berg River area (G10A with an allocation of 400m³/ha/a compared to 150m³/ha/a). This would make sense if the rain that fell in that quaternary drainage area stayed in that area. The baseflow to rivers in these mountain catchments are fairly high, which means that the higher abstraction reduces the volume of groundwater that discharges into the river. This in turn reduces the volume of water that flows in the Berg River. If some of the recharge to the Lower Berg River Aquifer System comes from the Franschhoek valley, this higher abstraction also reduces the recharge to the groundwater systems along its flow path.

Figure 16 shows the quaternary drainage areas of the Berg River catchment area (red polygons). The fault lines – inferred or properly delineated – are shown in orange. The sites represent the measuring stations along the Berg River. The management of water resources are easier when the area managed can be made as small as possible, but it is important to understand that it is part of a bigger system. The General Authorisations also comes with set general conditions that is part of the Gazette. It is not possible to add conditions if the specialist scientist feels that the area is sensitive and would require greater caution. The capacity to monitor compliance to the conditions is inadequate.



Figure 16: Quaternary drainage areas for the Berg River catchment with hydrological stations (Vermaak, et al., 2019b).

The cumulative impact of water use licence applications in close proximity is not taken into consideration. Each licence is evaluated on its own merits, but in this way the aquifer may be stressed beyond its capacity. Water use licence applications are seldom declined. One of the most frequent reasons used in declining an application has to do with groundwater resource availability, measured on quaternary drainage area scale. The Reserve is used as the measure of whether groundwater is available. It creates a dilemma for an application in G22C with an artesian borehole that almost washed away the foundation of the house and caused a nuisance for the neighbours that the water use licence is declined due to lack of groundwater availability. The quaternary drainage areas are linked to surface water catchments and groundwater often transcend these boundaries. G22D (Figure 10) forms part of the Cape Flats Aquifer. The recharge of the aquifer potentially comes from a wider area than just the one quaternary drainage area, as groundwater systems are controlled by geology, and therefore does not necessarily conform to surface water boundaries. This means that G22D May get its recharge from a number of other quaternary drainage areas adjacent and further afield. The Reserve for a single quaternary drainage area would make sense if the area only relied on the rainfall on that area for its recharge. The concept of stressed catchments does deserve further investigation and it may be necessary to develop a reliable stress index.

Table 5 shows part of a spreadsheet where groundwater availability (GRAII), registered water use (WARMS) and a stress index were used to determine how much groundwater are available per quaternary drainage area. Cells in pink is quaternary drainage areas with a deficit, the ones in yellow are borderline, and the few in white went into a double negative (G21B – the Atlantis aquifers). In the last column the comment “Compulsory Licencing” was added for quaternary drainage areas that were coloured in pink, yellow or white. Almost 60% of the quaternary drainage areas in the Western Cape are in deficit or borderline. This refers back to the section on groundwater availability and allocation. It seems that it would be necessary to institute compulsory licencing as soon as possible if permanent damage to the aquifers is to be avoided. The question on where the recharge to the Lower Berg River Aquifer System now becomes a burning issue. If a large amount of the recharge comes from the Franschhoek Valley with its numerous water-bottling plant and vineyards, it would have a huge impact in the long run on the groundwater availability in the Lower Berg River area.

There is a need to set criteria on which water use licence applications should be evaluated, by competent qualified officials, that understand the systems they are working in. The conditions for the licences on groundwater use cannot be set according to engineering principles, as groundwater cannot be managed like surface water. It would not be possible to give exact volumes, water levels or threshold values against which to manage the resource if you do not know how the system will behave. A pumping test only provides the first hint of the response of the aquifer on abstraction, but the rest is still unknown. Adaptive management will provide a way in which to manage the resource sustainable by monitoring its response to abstraction and changing the management in response. It would be a learning experience for all involved. Capacity to monitor all the new licences that have been awarded, remains a challenge.

GRAII is outdated, based on limited data that was estimated from maps. Yet it is the best we have and forms the basis for countless studies done by scientist and consultants working in the groundwater industry. It is the basis on which a lot of decisions are made in DWS. It is used in the Reserve calculation. It would thus seem that it is high time for a revision of the GRAII programme. The geohydrological maps are also outdated, as it was based on the GRAI data. It is a generalisation and extrapolation of data over a large scale.

Table 5: Stress index levels using GRAII data.

Quaternary catchment	UGEP (m ³ /a)	Stress Index 2017	2017 WARMS per Quaternary catchment	Difference of Recharge and GA2016 %		Difference of UGEP and GA2016 %		Difference of Recharge and GA Am 2016 %		Difference of UGEP and GA Am 2016 %	
				Normal (Mean)	Dry	Normal	Dry	Normal (Mean)	Dry	Normal	Dry
				Re	Re (dry)	UGEP	UGEP (dry)	Re	Re (dry)	UGEP	UGEP (dry)
G10A	22 935 600	0.16	3 638 049	83	79	63	54	83	79	63	54
G10B	13 214 800	0.05	612 800	83	79	66	57	83	79	66	57
G10C	15 794 700	0.37	5 841 401	58	46	7	-20	76	70	47	32
G10D	10 461 500	0.33	3 499 435	65	52	11	-32	83	77	58	37
G10E	3 280 970	1.48	4 856 102	53	35	-53	-228	79	71	31	-48
G10F	2 643 200	0.11	278 035	59	41	-63	-217	99	98	95	89
G10G	10 410 500	-	-	72	64	46	29	80	75	63	51
G10H	1 323 560	2.30	3 041 119	-34	-99	-364	-894	69	54	-7	-130
G10J	101 513	2.75	279 273	24	-11	-449	-12 994	98	98	88	-175
G10K	5 062 690	1.40	7 096 793	-41	-111	-224	-389	60	39	7	-40
G10L	8 289 660	0.38	3 145 517	8	-37	-135	-255	90	85	75	62
G10M	9 240 830	0.35	3 275 551	-1	-66	-124	-261	90	84	78	65
G21A	4 977 610	0.15	765 260	47	19	-11	-73	95	93	90	85
G21B	1 676 290	3.63	6 082 760	-2	-52	-535	7 681	42	13	-263	4 429
G21C	1 123 770	1.19	1 333 515	26	-6	-162	-345	80	72	30	-19
G21D	1 982 440	4.16	8 242 104	-36	-96	-327	-682	28	-4	-127	-316
G21E	1 870 820	2.10	3 924 589	34	5	-146	-535	78	69	19	-110
G22H	4 583 890	0.20	934 244	36	13	-51	-119	83	77	60	42
G22J	8 252 260	0.07	553 308	75	68	47	31	75	68	47	31
G22K	3 567 360	0.10	355 702	64	50	27	1	84	78	68	56

2.3 Adaptive Management as management strategy

The effective management of water resources is important to sustainable development, but it rests on good governance being in place. Governance rests on two core values. The first value is inclusiveness that ensures that all members of a group receive the same treatment, while the second is accountability. Accountability means that those in authority answers to the group that they serve. Governance processes are used in decision-making about water storage, types of water use, regulating the extraction of aquifers, regulation on the discharge of process water, and the allocation of water between competing uses (including the environment to ensure basic environmental services) (Bucknall et al., 2006). Governance often relies on policies and legislation that tends to generalize water resource system, which makes it difficult to implement in the real world where you get exceptions to the generalized concepts. This is the reason why it is generally

assumed that the same management programme will fit different systems, without checking the site-specific details.

Management traditionally entails the making of a single definitive decision even though there may be gaps in the information available, or uncertainty about the system that is involved in the decision (Susskind, et al., 2011). Adaptive management developed in the early 1970s to apply continuous involvement in decision making around natural resource management (Holling, 1978). It emphasises learning through the monitoring of management strategies. This then enables the management strategies to be adjusted to changing conditions and new information as it becomes available (Holling, 1978; Williams, Szaro & Shapiro, 2009; Doremus et al., 2011). Adaptive management and collaborative planning are seen as ways to address deficiencies in the conventional regulatory decision-making process (Susskind & Secunda, 1998; Williams, Szaro & Shapiro, 2009; Innes & Booher, 2010).

Adaptive management can be defined as a “structured, iterative process of robust decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring.” (Holling, 1978). It is also known as adaptive resource management or adaptive environmental assessment and management. Decision making using the adaptive management principles makes it possible to meet one or more resource management objectives while information is collected that can be used to improve future management. Thus, according to Holling (1978) it is a tool that can be used to change a system and simultaneously learn about the system. Adaptive management is a long-term management outcome, as it uses continuous learning on which to base management decisions. The challenge is to find the correct balance between gaining knowledge and the improved management of the system to ensure the best outcomes in the short-term using current knowledge (Allan and Stankey, 2009).

The Conservation Measures Partnership (2013) developed an adaptive management programme that can be adjusted for various conservation programmes (see Figure 17). It is based on the general principles of involving stakeholders, development and cultivation partnerships, embrace learning, document decisions and making adjustments to the programme as necessary. They have divided the programme into five steps. It is important to specify the parameters that would be needed in developing the programme for the management of the system that would be managed.

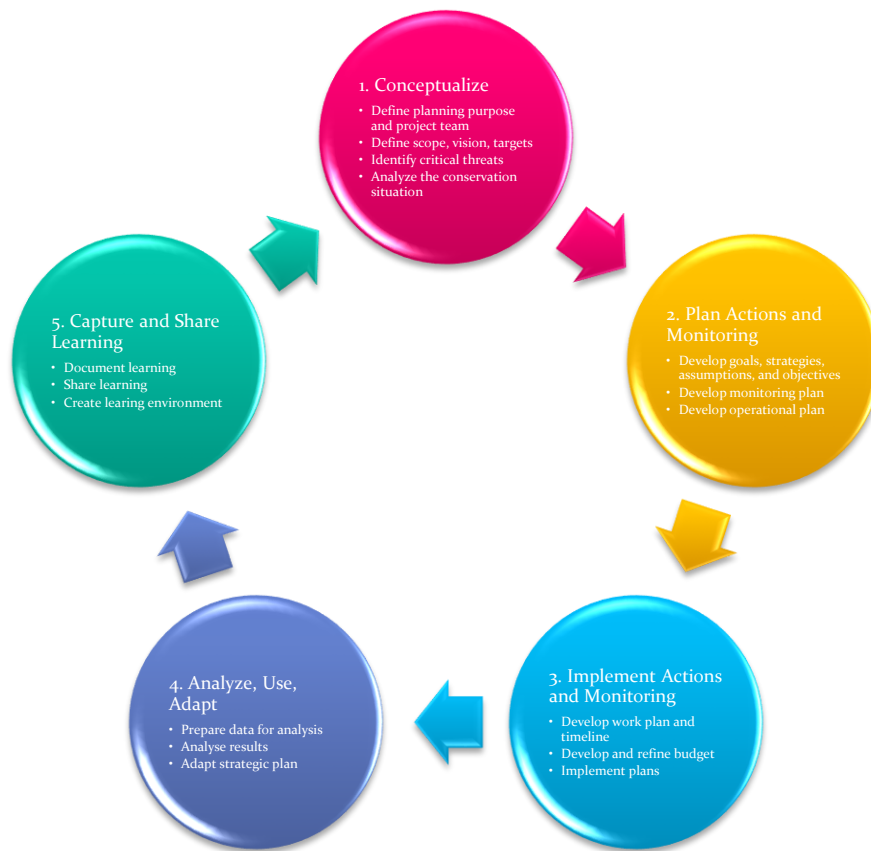


Figure 17: Adapted from CMP Adaptive Management Cycle (2013).

Specifying the basic parameters that goes into the adaptive management programme should be identified at the beginning of step 1 (Conservation Measures Partnership, 2013), as this is needed for the design of the programme. There are some assumptions made in the programme, which includes that the beginning of projects is usually preceding step 1. This means that some information will, in most cases, already be available at the beginning of the adaptive management process as set out by this programme.

There is already a number of programmes and processes that is used for groundwater development projects. The first is the planning life cycle (Figure 18) that shows the higher-level (national or regional government) planning for a groundwater resource development. Most groundwater schemes follow the process up to point 5, and from there most developments seem to skip the next three steps. There is thus a need to focus more attention to steps 6 to 8.

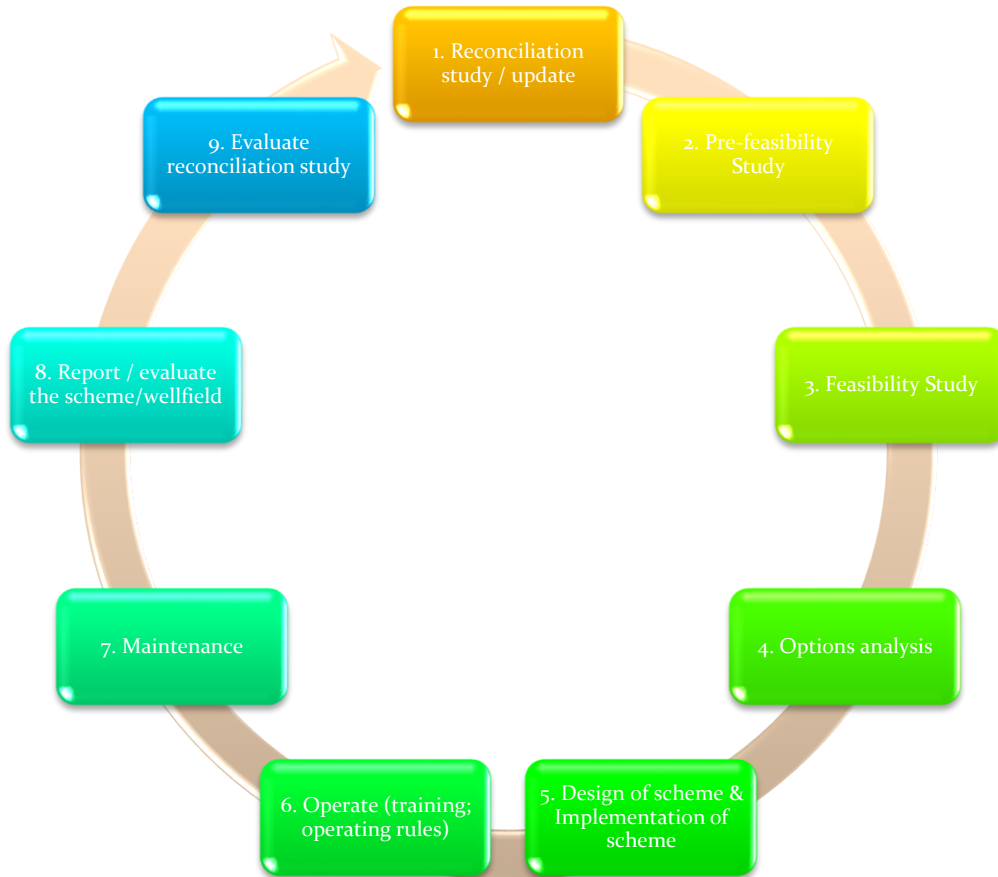


Figure 18: Planning life cycle (DWS, 2017; Fourie, 2019).

The following steps are included in the groundwater development process at a lower level (usually the municipal/local government level):

- Conceptualisation
- Reconnaissance
- Pre-feasibility
- Design
- Construction
- Operation

In this development cycle the process stops at the operation of the wellfield. It does not include anything else. This means that there is no monitoring, evaluation or adjustment in the operational plan.

More detailed steps are given by the project process diagramme (Figure 19), which gives a fairly detailed overview of the development of the groundwater scheme or wellfield, but the operation and maintenance entails far more than what is included here. It also leaves no room for adaptive management in the process but goes straight to the auditing and compliance issues. It does, however, include the authorisations required for the development and operations of the scheme.

Public participation and monitoring of the potential impacts of the groundwater development on the environment and other groundwater users are not included in any of three models presented.



Figure 19: Flow diagram of the project process (DWS, 2017; Fourie, 2017; Fourie, 2019).

2.3.1 Examples of Adaptive Management

Adaptive management has been used in a number of conservation projects that included wildlife protection, forest ecosystem forest ecosystem protection, coastal protection and restoration and fish conservation from overfishing. Adaptive management can also be used to address the possible impacts of climate change. It has also been used in the management of natural resources, such as

water, land, and soil. In this publication two examples will be used – one example will be on water resource management and the other a local adaptive management model that is already in place and showing some successes. The first example illustrates how the development and management of groundwater resources in Denmark follows the principles of adaptive management. The second example look at the management of the coastal zone of the Saldanha Bay-Langebaan Lagoon through the Saldanha Bay Water Quality Trust Forum, since it links to the study area for the Lower Berg River Aquifer System and coastal aquifers in general.

2.3.1.1 Denmark – groundwater mapping and protection zones

One of the examples where adaptive management worked in the management of water resources can be seen in the country of Denmark (Danish Ministry of the Environment, undated). This came about as a result of the strict enforcement of regulations for more than four decades by the local, regional and national authorities. The first Environmental Act came into effect in the early 1970s and was meant to improve the water quality in open water bodies in the country. The different sectors in the country contributed to the success of the efforts to reduce the discharge of nutrients and organic matter with the main drive from the public authorities (especially the municipalities), industry and agriculture. The approach to water management in Denmark can be seen in Figure 20. The starting point will be to collect information and data on the current status of the resource, the nutrient load, and its sources, etc. This information is then used to do proper planning and where necessary to make political decisions about the measures that need to be taken to address the problem. After the implementation of the measures, the situation is again assessed to determine whether the status of the resource has improved, and the objectives reached or whether additional measures would be required.



Figure 20: General approach of water management used in Denmark (Danish Ministry of the Environment [a], undated).

Danish site-specific groundwater protection strategy based on three steps (Danish Ministry of the Environment [b], undated):

1. Spatially dense hydrogeological mapping based on new geophysical surveys, survey drilling, water sampling, hydrological modelling, etc., aimed at facilitating the establishment of site-specific protection zones. These zones are directed at both point sources and diffuse sources of pollution within the entire groundwater recharge area and are to supplement the traditional protection zones around wells. Vulnerability is interpreted in relation to the local hydrological and chemical conditions.
2. Mapping and assessment of all past, present and possible future sources of pollution – both point sources, and diffuse.
3. Preparation of an action plan stipulating politically determined regulations for future land use and remediation of polluted sites. The plan is to be evaluated through a public planning process with a high degree of transparency and public participation. Moreover, the plan must include a timetable for implementation, and a description of who is responsible for implementing the plan.

One facet of the Danish system of groundwater development that needs to be included in all groundwater developments is the involvement of stakeholders in the process (Figure 21), showing adaptive management even in the mapping of the resource. The 7 steps that are followed are showed in Table 6. In this model, stakeholders are involved in the screening process and helps to prioritise areas and identify issues. The municipality, regional government and waterworks are involved in the start of the programme, while the landowners, well-owners and the press are involved in the data collection phase. The municipality is involved in analysing the results, which is then shared with the general public in the closing of the project. If the results show that there are still gaps, the cycle is repeated. The cooperation and involvement of stakeholders can help avoid delays, provide guidance in planning and decision making and lead to less misinformation about developments among the general public. This is one of the expensive lessons that was learned during the recent drought in Cape Town, where lack of inclusion of especially the environmental stakeholders led to delays, misunderstandings and large amounts of misinformation about the groundwater developments that was intended to improve water security to the water users.

Stages of a mapping project

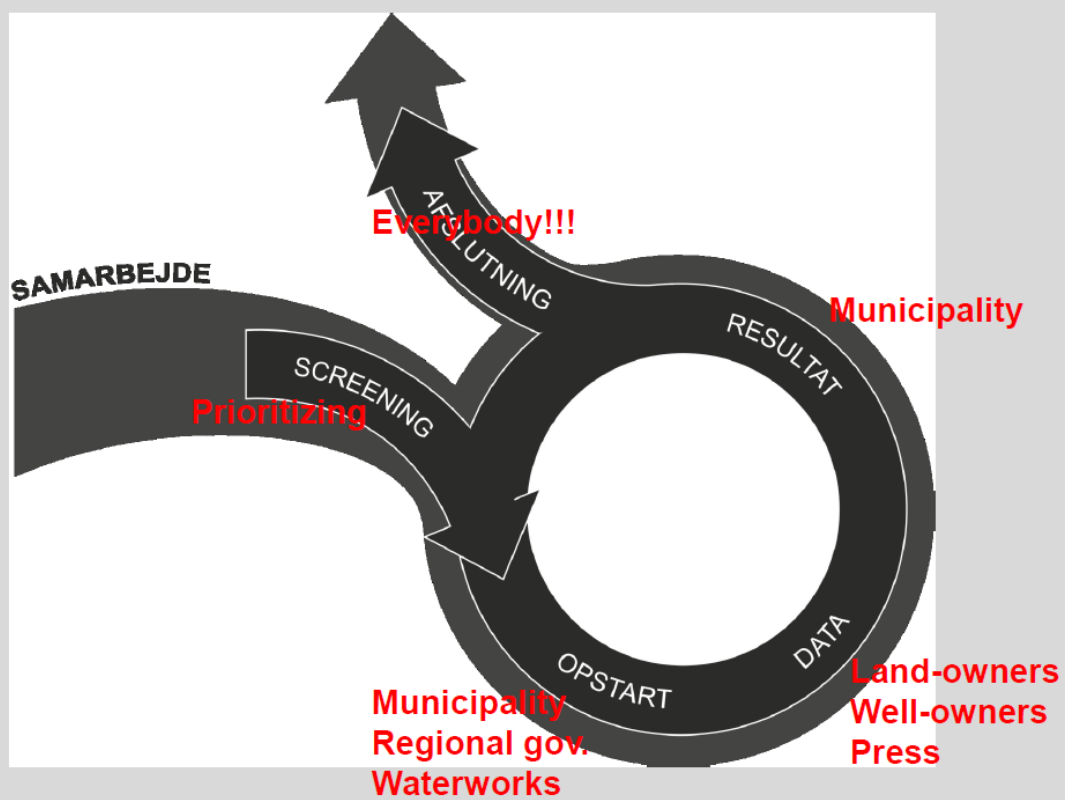


Figure 21: Public participation in the different stages of a groundwater mapping project (Jensen, 2017).

Table 6: Groundwater mapping is always performed in 7 steps, but the scale of each step may vary between mapping areas (Miljøministeriet, Naturstyrelsen, 2012).

The Danish Ministry of the Environment’s Groundwater Mapping Process	
Step 0	Project Startup Establish a project group, prepare project description and stakeholder analysis, establish technical follow-up group and contact with affected parties and municipalities
Step 1	Analysis of existing data Collection of existing knowledge about water extraction, land use, sources of pollution, geophysics, geology, hydrology and groundwater chemistry
Step 2	Detail mapping of geology, hydrology and chemistry Drilling registrations, geophysical measurements, drilling and sedimentology, hydrological measurements, water and sediment chemistry, geological and hydrological models
Step 3	Detail mapping of land use and pollution sources An overview of the current land use and explanation of whether land use can be groundwater protection or potential groundwater pollutants. Perform the calculation of nitrate leaching and describe contaminated grounds
Step 4	Defining areas of action and revision of other area boundaries Preparation and updating of OSD, OD, NFI, ION, map and recovery maps groundwater formation, groundwater formation
Step 5	Suggestion and Reporting Preparation of final statement, with proposals for efforts and proposals for monitoring. Data and card reporting
Step 6	Project termination Data registration is completed: Stam Card, Report Database, Environmental Portal and journaling. Drills are lit, looped and / or transferred. Rounding off stakeholder involvement

2.3.1.2 Saldanha Bay Water Quality Forum Trust (SBWQFT)

The Saldanha Bay Water Quality Forum Trust had its origin in the need for integrated monitoring and management of the Saldanha Bay – Langebaan Lagoon system (van Wyk, 2001). This system is an important natural resource that provides a habitat for endangered birds and fish, with a number of towns, an export harbour and various industries that has an impact on the integrity of the ecosystem.

The management of the system and the various activities that may potentially impact it is vested in different government departments on three levels of government. Each of these departments has their own legal framework that mandates how activities and systems should be managed. The aim of the Saldanha

Bay Water Quality Trust Forum when it was established in 1996 was community driven integrated management of the Saldanha – Langebaan coastal zone. The Saldanha Bay Water Quality Forum Trust is a voluntary organization that brings together representatives of various organs of State, local industry and other relevant stakeholders and interest groups, giving impetus to the monitoring and understanding of changes in the health and ecosystem functioning of the unique ecosystem (van Wyk, 2001; Clark, et al., 2018). It was thus important to understand the bio-physical characteristics of the water resources, and to have an idea of what the water quality needs of the different water users are. It was further important to manage the pollution impacts of human activity and the interaction between the different groups (van Wyk, 2001).

Van Wyk (2001) divided the water quality management process into three phases (see Figure 22). The first phase was the Objective Phase where the characteristics of the water resources was determined, and quality objectives developed that would be used in the management of the resource. This was followed by the Monitoring Phase where a monitoring programme was developed and implemented. The next phase is the Management Phase that includes data analysis, gap analysis and the formulation of a water quality management plan.

The monitoring programme includes the direct monitoring of a number of important ecosystem indicators (initiated by the SBWQFT in 1999), which include water quality (faecal coliform, temperature, oxygen and pH), sediment quality (trace metals, hydrocarbons, total organic carbon (TOC) and nitrogen) and benthic macrofauna. The number of parameters monitored over time and the project has led to the commissioning of a “State of the Bay” technical report series in 2006. This report has been produced every year since 2008 and presents data on parameters that is monitored the SBWQFT and other bodies that include government, private industry, academic establishments and NGOs (Clark, et al., 2018).

It is clear from the monitoring and the State of the Bay reports that developments in Saldanha Bay and Langebaan Lagoon have had an inevitable impact on the environment over the last thirty years. Most of the trends tend to be on the negative side, but there had been some successes during the history of the SBWQFT. There is, however, still much that needs to be done to manage the system efficiently and to restore the health of the bay. A holistic approach to the management of the system is very important and only through regular monitoring of all the parameters can the success of the programme be determined (Clark, et al., 2018). One of recent developments was to include groundwater into the analysis and reporting. Recent developments in the area and the recent drought brought the importance of the coastal aquifers in the area to the attention of the general public. It is thus important

to develop an adaptive management strategy for the Lower Berg Aquifers System that will add to the already existing work done by the SBWQFT.

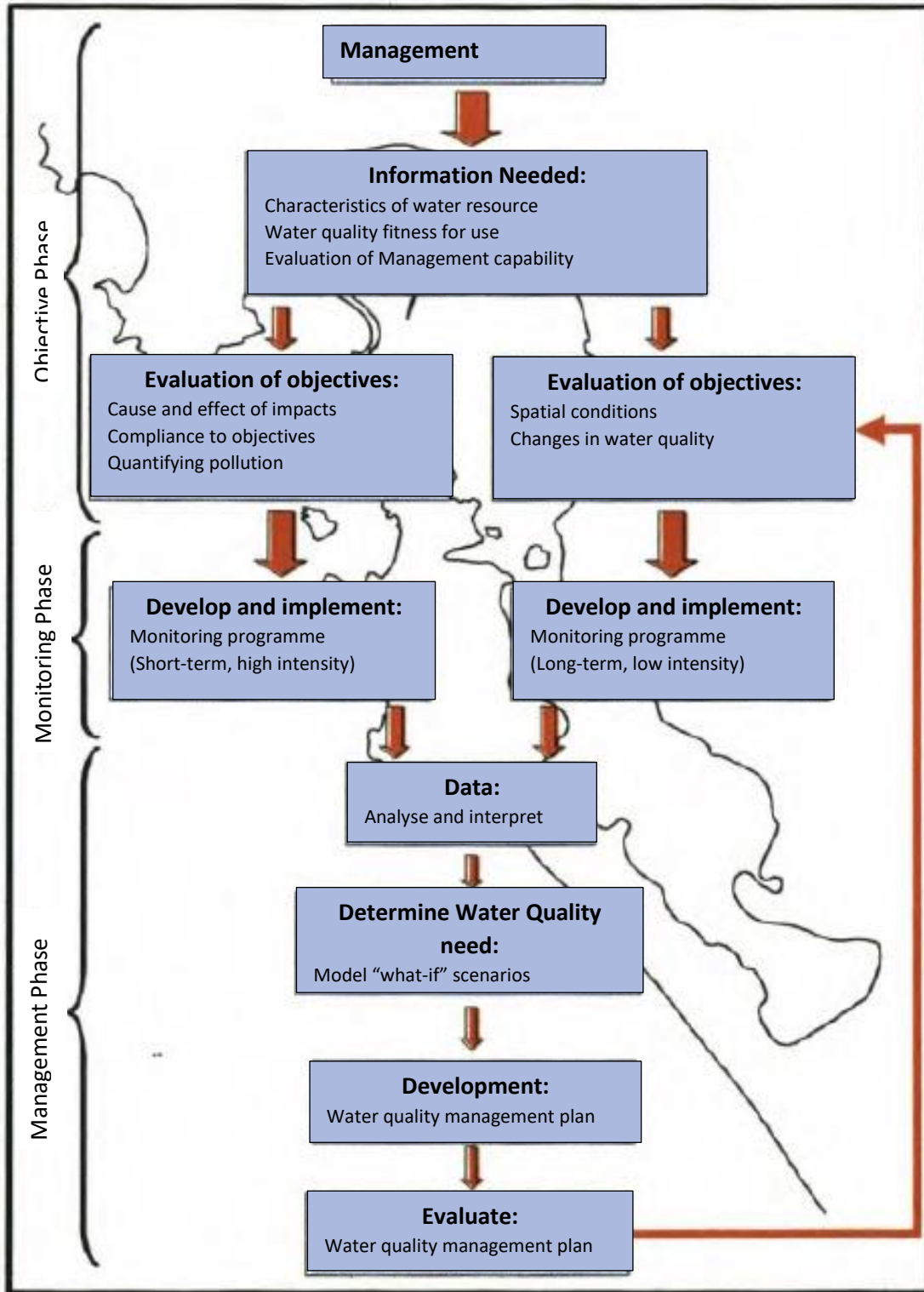


Figure 22: Water quality monitoring and evaluation process (adapted from van Wyk, 2001).

2.3.2 Why Adaptive Management for aquifers?

In the management of dams and other surface water systems, it seems to be so much easier. The volume of water that enters the system should theoretically be available for allocation and use. The volume of the dam, shortly after construction is a known entity, and can thus be managed with precise measurements. The tendency is to manage water resources on engineering principles, but engineering principles does not apply to groundwater systems.

Operating rules are set for the management of water resources, because it makes it easier to leave the management of the resource to people that may not have the scientific understanding to know that maybe this is not the optimal way to manage the resource. This may potentially lead to problems and strengthens the notion that groundwater is an unsustainable water resource. The problem lies in applying the wrong solution to the management of the groundwater resource.

Groundwater is somewhat of a dark horse when it comes to the management of water resources, because it is more complex and not visible. It is an oversimplification to say that the volume of recharge received in a year will be the volume that is available for allocation and use. Groundwater, like many other natural sciences, is inexact with lots of unknowns. One of the greatest uncertainties in groundwater is recharge. Recharge of an aquifer may come from distant sources, in addition to the local recharge. This means that there is a potential time delay between rainfall events and the augmentation of the system from the water that infiltrated the groundwater system. It is unknown how much of the rainwater infiltration actually reach the water table, and how much of that actually reaches the study site. This is just some of the unknowns just around the recharge of groundwater systems. It is further not possible to determine the amount of recharge with the volume that is available for abstraction from an aquifer.

The Langebaan Road aquifer unit is a good example of the uncertainties around the groundwater system, and how those uncertainties will inevitably affect the management of the groundwater resource. The Langebaan Road wellfield was established on the Langebaan Road aquifer unit in 1998 using the conceptual model established by Timmerman (1985a, b, c, 1988). This provided a volume that was stored in the system, together with an estimated recharge volume, as well as aquifer boundaries. This provided the potential volume that may be abstracted by the West Coast District Municipality, who received a licence to abstract 1.4 million m³/a from the aquifer. Fourie (1998), one of the members of the community, showed that the abstraction of groundwater would impact the Langebaan Lagoon, which is

dependent on the outflow of groundwater from the Elandsfontein aquifer unit at Geelbek.

Since the conceptual model from Timmerman indicated a no-flow boundary between the two aquifer units, this concern was considered of no importance. The model built by CSIR also showed that there would only be a drawdown of 5m for the duration of the wellfield and confirmed the idea that the abstraction will not impact the Langebaan Lagoon (Weaver, et al., 1997). Historical data showed that the actual drawdown was 11m and that there was a noticeable drop in water levels in the Elandsfontein aquifer unit, with a time delay of up to 2 years before the impact could be seen. The actual impact on the Lagoon was never quantified, as no monitoring had taken place in the area. Proper monitoring at the relevant sites could have and should have acted as a warning sign, and management could thus have been adjusted to limit impacts to an acceptable level. Existing models should also have been updated as more information became available. Unfortunately, most models, still used the conceptual model as set out by Timmerman. The work that was done on the Berg WAAS project for the Department of Water Affairs in 2008 still used the concept of the no-flow boundaries postulated by Timmerman in 1985. Woodford had by this time already indicated that there should be a link between the Langebaan Road and Elandsfontein aquifer units based on the results of monitoring data. It was only after 2012 with the publication of the report by Roberts and Siegfried (2012) that several geohydrologists began looking at the system differently. The model by Seyler (2016) was one of the first numerical models that incorporated the idea of hydraulic connectivity between the Langebaan Road and Elandsfontein aquifer units. Seward, et al (2006) motivated for the use of adaptive management after evaluating the factors that will affect the sustainable management of groundwater (Table 7). Possible solutions to the limiting factors were added to the arguments presented, but there will still be uncertainties, which makes adaptive management a more promising strategy for the management of groundwater.

Table 7: Factors that influence the sustainable management of groundwater (after Seward et al., 2006).

Limiting factors	Explanation	Possible solutions
Knowledge of groundwater use	Groundwater use not measured; estimated from visible irrigation; conjunctive use complicates estimation; does not include other uses, such as stock watering, agri-processing, etc.	Compulsory metering (GG 41381 of 12 Jan 2018)
Regional status of groundwater resources	Intensive monitoring in some areas, with little to no monitoring in others; regional monitoring sparse or non-existent	Water users to monitor own resource (citizen science); data to be shared and stored in central data base
Groundwater parameters variable over space and time	Difficult to upscale determinations from single point to groundwater basin; heterogeneous nature of aquifers; ranges in conductivity of water through aquifers; temporal variability in rainfall in semi-arid climates; spatial variability of soil characteristics, topography, vegetation and land use lead to variability in recharge estimation. Not possible to predict future outcomes with certainty.	Improve monitoring Improve recharge estimations Regular analysis of monitoring data
Ability to predict impacts of groundwater abstraction on surface water and ecological systems	Uncertainties about groundwater-surface water interactions Link between groundwater and ecology poorly understood Environmental impacts of groundwater use uncertain.	Improve monitoring of relevant environmental parameters
Prediction of future outcomes	Models are used to predict outcomes, but it was found that models cannot accurately predict the future. Causes for this poor prediction ability of models include the range of parameters are often larger than included in the model; an incorrect choice of conceptual model; what took place in the	Suite of scenarios; Models only predict future with reasonable confidence for a period equal to historical record – consistent long-term monitoring data needed Regular review of models, with updates where necessary

	real system were not anticipated in the scenarios	
Monitoring data often not diagnostic		Regular analysis of monitoring data Gap analysis to gain better understanding

2.4 Summary

Coastal aquifers can be found around the globe, where their importance is not dependent on size. In some countries they form major part of the country (Netherlands and Denmark), while in others, they only form a small part of the country (South Africa). Their importance also does not just lie in the volume of water that it stores, or the amount that may be abstracted to provide water. The importance of these aquifers lies in the ecosystem functions that it fulfils. It is the transition, the ecotone as it were, between the terrestrial and the marine environments. The importance of coastal aquifers has been recognised in a number of countries and measures has been put in place to manage them through legal frameworks and other management practices. Chapters 3 to 6 will provide information on one complex coastal aquifer system on the west coast of South Africa, while Chapter 7 will look at adaptive management using groundwater management principles for the sustainable management of the Lower Berg River Aquifer System and other coastal aquifers.

Chapter 3: Study Area



G46092 and G46092-RF (9 July 2015)

3.1 Introduction

In 1972 when the Cape Departmental Council asked the Geological Survey that a study be undertaken into the development potential of groundwater for industries in urban areas in the Mamre area (Vegter, et al., 1976). There was also a need to find out what the potential for pollution by industries and sewage works in the Mamre development would be. The geological and geohydrological investigation of the Cenozoic sediments by the Geological Survey (Department of Mines) moved further north towards the Lower Berg River area that included the Langebaan Road and Geelbek areas in 1974. The Department of Water Affairs: Division Geohydrology took over the work in 1979. Part of the reason for the study was to supply the Saldanha harbour project with water (Timmerman, 1988).

From 1974 to 1985 a number of geohydrological investigations have been carried out in the area between Velddrif, Hopefield, Darling and Langebaan by the Department of Water Affairs and Forestry to determine the potential of groundwater resources as an additional water source to the Berg River (Woodford, 1999). The early work (1974 - 1977) included geophysical prospecting with refraction seismic and gravimetry (Botha and Thompson, 1978) followed by cable tool percussion drilling for calibration boreholes. The geophysical methods failed to determine the thickness of the Cenozoic sediments as it was difficult to distinguish between the

unconsolidated sediments and the weathered bedrock. The drilling provided valuable information on the sedimentology, geology and hydrogeology of the area. Free flowing artesian wells near Langebaan Road led to the declaration of the Saldanha Subterranean Government Water Control Area (SSGWCA) in September 1976. One of the reasons for the declaration was to minimize the interference during the further investigations in the area (Vandoolaeghe, 1983). The other reason was to protect the water resource for future use since it was recognised as a strategic resource (Timmerman, 1985a; Woodford, 1999). Further studies identified the “Lower Berg River Super-Unit” with the possibility of supplying fresh water at a rate of 52 Mm³/a (Timmerman, 1985a; Woodford, 1999).

This chapter will provide more information about the study area, looking at the research that formed the basis of this thesis.

3.2 Location

The study area is about 100km north of Cape Town, along the west coast of South Africa. Figure 23 shows the extent of the study area. It includes the quaternary drainage areas of G10K, G10L, G10M, G21A and half of G30A. The area is approximately 5 800km² with a perimeter of about 45km.

Most of the area is covered with unconsolidated sediments, with granite outcrops, Malmesbury shale and Table Mountain Group sandstones making up the rest of the surface geology. The Berg River is the major river in the area, with its tributaries, the Sout, Groen, Brak and Kuilders Rivers. Other areas include the Papkuils River, the Modder River and its tributary, the Kransduinen River, as well as a number of smaller coastal rivers that are mostly unnamed.

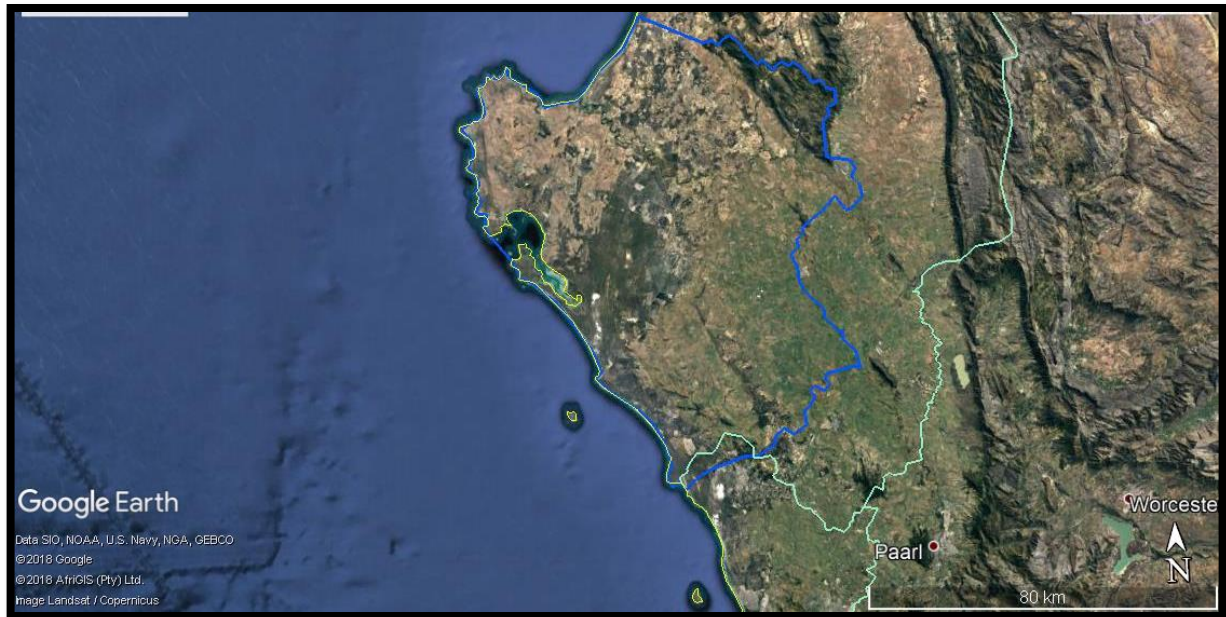


Figure 23: Satellite image showing the study area.

The study area falls almost exclusively within the West Coast District Municipality, with the major towns in the area being Vredenburg, Hopefield, Malmesbury, Darling, Langebaan, Langebaan Road, Yzerfontein and Aurora. The area is mainly a farming area with tourism, fishing and a growing industrial area. The expansion of the harbor in Saldanha Bay allows for the anchoring of heavy bulk carriers, that are carrying iron ore that comes from the mines in Sishen. Langebaan Road is the training center for the South African Air Force (Timmerman, 1988).

3.3 Climate

The climate is Mediterranean (Timmerman, 1985a; Timmerman, 1988; Woodford, et al., 2003) with hot, dry summers and cool, wet winters. It is to a great extent the product of the major pressure and wind systems in the Southern Hemisphere (see Figure 24) (Heydorn and Tinley, 1980). These synoptic systems drive the seasonal rainfall distribution over Southern Africa through their north-south migrations. This includes the Intertropical Convergence Zone (ITCZ), the Subtropical High Pressure Zone (SHPZ) and the Temperate Zone (Antarctic low pressure system). Seasonal airborne moisture mass distribution over Southern Africa is highly variable, with prominent summer/winter cycles. The summer and winter atmospheric conditions are shown in Figure 25, with the annual north-south migration of the three climate zones and the pathway of the synoptic systems that drives the various rainfall events over South Africa during the winter and summer rainfall seasons (Van Wyk, et al, 2011).

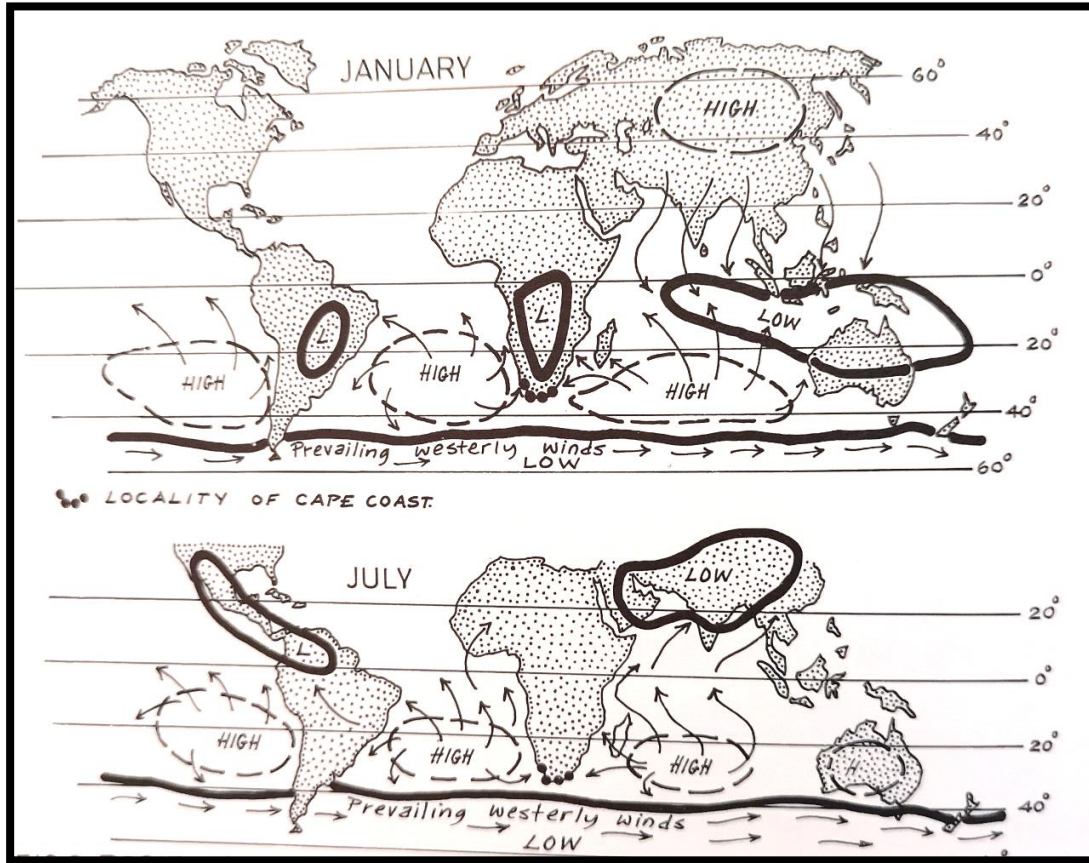


Figure 24: Position of the Cape Coast in relation to the major pressure and wind systems of the Southern Hemisphere (Heydorn and Tinley, 1980).

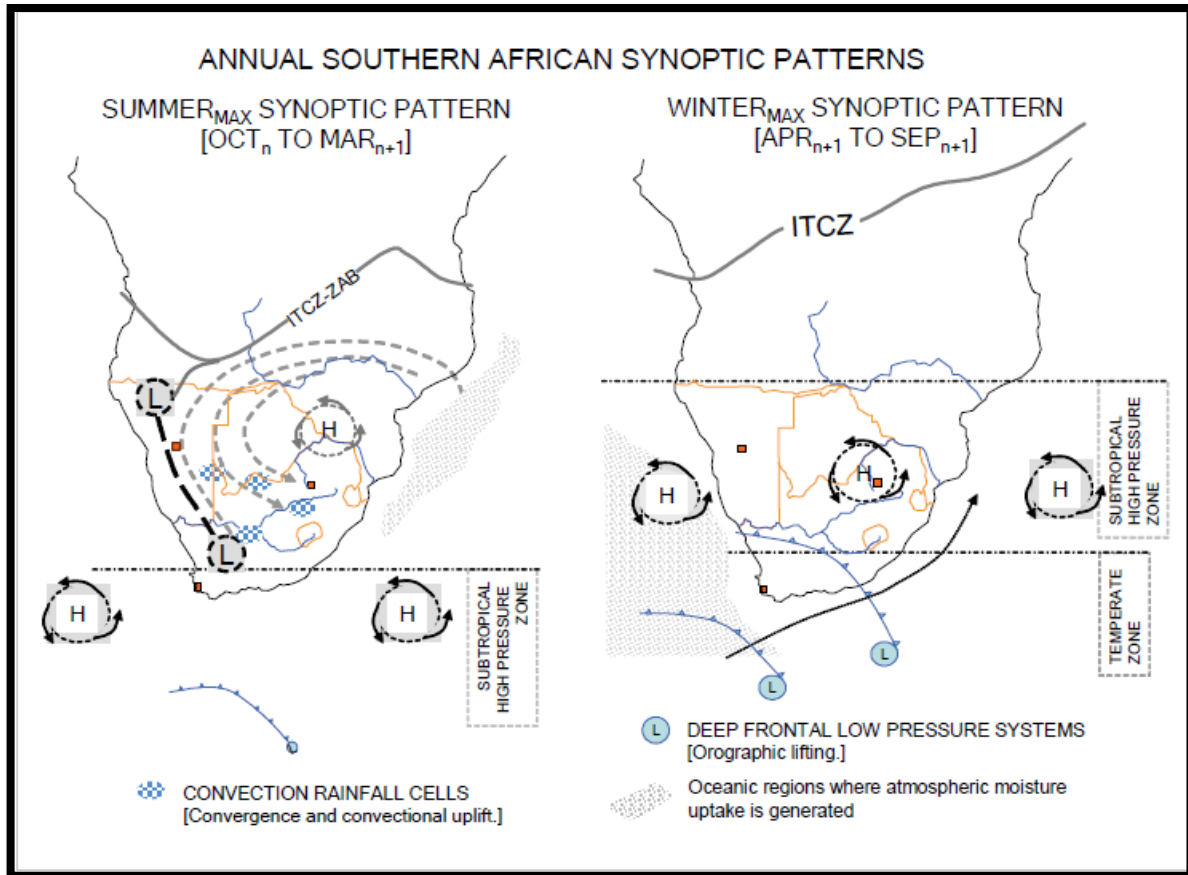


Figure 25: Synoptic patterns over Southern Africa during summer and winter seasons in relation to the generation of airborne moisture and the general migration pathways (van Wyk, et. al., 2011).

The proximity of the study area to the Atlantic Ocean has a very strong influence on the temperatures in the area, and extreme temperature variations are not experienced along the coast. The summers are dry and warm, with moderate to strong southerly winds blowing in the afternoons (Timmerman, 1988).

3.3.1 Temperature

The temperatures of the study area are usually moderate with very little extremes because of its proximity to the Atlantic Ocean and the cold Benguela current. The average daily maximum is around 18°C near the coast and 21°C inland. Average daily temperatures vary between 12°C at the coast and 10°C inland (Timmerman, 1988). Summers are dry and warm, while winters are cool and wet.

3.3.2 Wind

The prevailing winds are moderately strong southerly winds in the afternoons, while the dominant wind direction during the rainy winter season is northwesterly or southwesterly.

3.3.3 Evapotranspiration

The potential evapotranspiration is high during the dry, hot summer months. It would be influenced by the higher temperatures and the wind. Actual evapotranspiration may be lower as a result of lower phreatic water levels and the adaptations of the natural vegetation to this climate. Potential evapotranspiration is lower in winter as a result of the lower temperatures and the higher cloud cover. The mean annual potential evaporation, as measured with A-pan for the area is between 1800 – 2400mm per annum (Schultze, 1997; Woodford, et al., 2003).

3.3.4 Humidity

The humidity of the study area is affected by the proximity to the coast and mist banks form along the coast. These banks seem to be more prevalent during the summer months.

3.3.5 Rainfall

Most of the rain falls during with winter months, with the rainy season beginning in April lasting through to October. Rain can occur in the summer months but is not a general occurrence. The dominant wind direction during the rainy season is northwesterly to southwesterly (Timmerman, 1985b; Timmerman, 1988). Storms that contribute significantly to the groundwater body is rare, with most lost almost immediately by interception, direct evaporation and plant consumption (Noble, 1976).

Precipitation decreases from south to north and from east to west (See Figure 26 and Figure 27, as well as Table 8). The mean annual precipitation (MAP) for Figure 26 were interpolated from Schultze (1997), and the rainfall stations used for calibration are given in Table 8. Orographic conditions are the dominant factor in the latter. The average rainfall in the south is around 320mm per annum, decreasing to 280mm per annum in the central area. The rainfall average at the foot of the Table Mountain Sandstone escarpment north of the Berg River is about 350mm per annum (Timmerman, 1988; Woodford, et al., 2003). Mist adds to the precipitation along the coast.

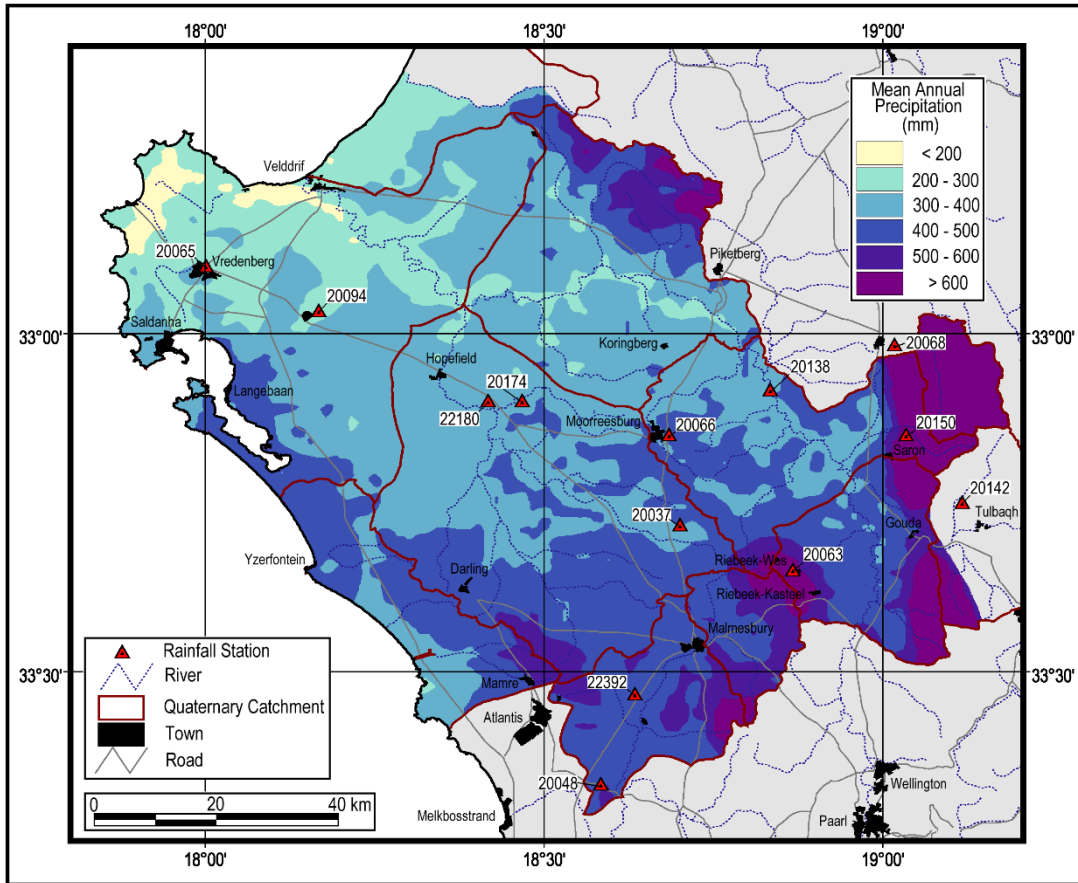


Figure 26: Mean Annual Precipitation of Study Area, showing Rainfall Stations used to calibrate the original CCWR MAP dataset (Woodford, et al., 2003).

Table 8: Mean Annual Precipitation at Calibration Rainfall Stations (Woodford, et al., 2003).

Station Number	Locality	Record Length	Mean Annual Precipitation (mm)
Vredenburg Ko-op (20065)	Vredenburg	1973 - 1988	317.0
Langebaan Road (20094)	Langebaan	1989 - 1992	283.5
Koperfontein (22180)	Hopefield	1996 - 2001	348.2
Moreson (20174)	Hopefield	1989 - 1994	344.7
Porterville (20068)	Porterville	1973 - 2001	524.4
De Hoek (20150)	Saron	?	616.0
Rooihogte (20138)	Porterville	1983 - 1995	390.0
Moorreesburg Ko-op (20066)	Moorreesburg	1973 - 2001	413.5
Langegewens Proefplaas (20037)	Moorreesburg	1964 - 2001	399.8
Riebeek-Wes Ko-op (20063)	Riebeek-Wes	1973 - 1996	556.5
Skaapkraal (22392)	Malmesbury	1997 - 2001	476.7
Philadelphia (20048)	Philadelphia	1969 - 2001	451.8
Waveren (20142)	Tulbagh	1984 - 1992	836.6

* Source: Institute of Soil, Climate and Water, Agromet, Pretoria.

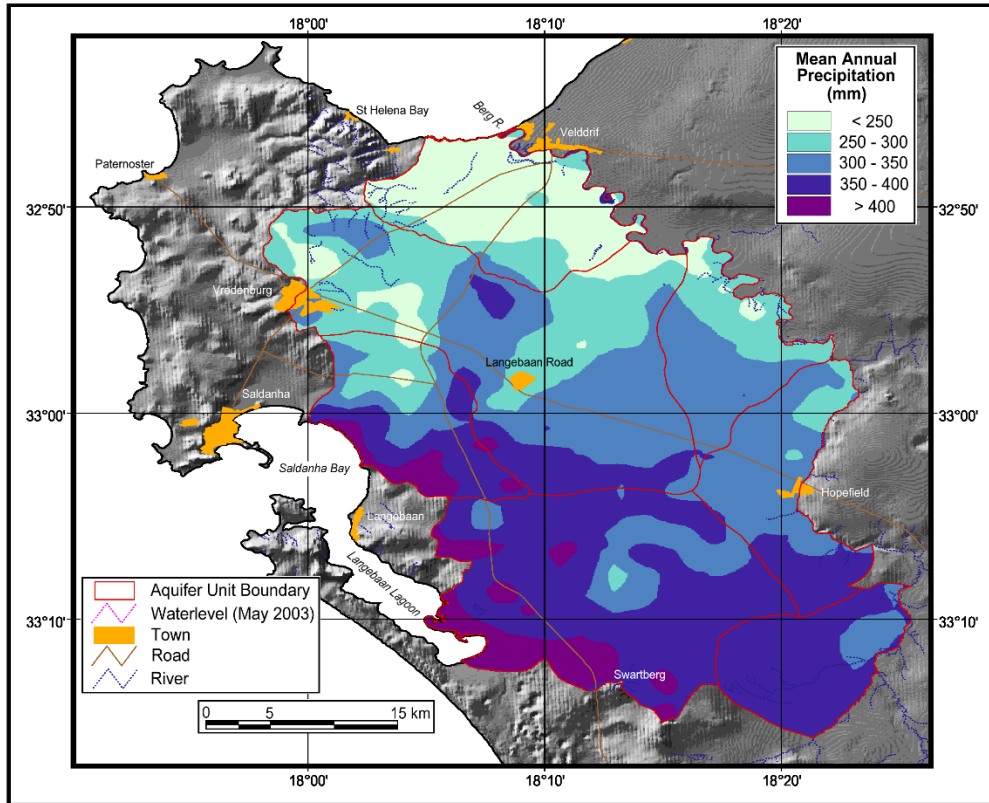


Figure 27: Mean annual rainfall for the central part of the study area (Woodford and Fortuin, 2003).

3.4 Topography

Narrow, steep sandy beaches give way to a continental terrace which extends up to 40km inland, with a landscape that is not greatly variable, except for the mountains to the east (Figure 28 and Figure 29). Sand covered plains, fixed dunes, surface limestone ridges and some unvegetated dunes characterise the area. Granite and related intrusives is found in the Vredenburg headland, the Darling hills and some isolated koppies, and can reach heights of up to 450m. The topography is otherwise generally flat to slightly undulating (Timmerman, 1985b). The area is covered by unconsolidated dune sands, which are completely vegetated (Timmerman, 1985a). The highest parts of the area are in the east around Hopefield with a height of about 100 m, with a levelling off towards the Berg River in the north and the coast in the west. A topographical watershed is found in the west with passages through it (Vegter, et al., 1976). The Langebaan Road landscape is characterised by a lack of relief features and has an average elevation of 35m above sea level (Timmerman, 1985a).

Timmerman (1988) describes six different landscapes for the area. The first of these is the young dunes, that is strips of unvegetated to partially vegetated dunes that

vary in height and can be found behind the beachfront. The second landscape type is the Sandveld, that forms a hummocky landscape north of the Berg River behind the coastal dunes. These sandy dunes are old dunes that have been stabilized with vegetation and are associated with small salt pans. The Sandveld covers the entire southern and eastern parts of the area south of the Berg River, reaching an altitude of 95mamsl west of Hopefield. These old dunes are arranged along a north-south axis between the Berg River and Yzerfontein and are a function of the dominant wind direction at the time of deposition (Visser and Schoch, 1973).

The next landform type is the old calcretized dunes that can be found to the south and east of Langebaan Lagoon. These dunes are more prominent than the Sandveld dunes as they are higher reaching an altitude of 150mamsl. The younger dunes that are not stabilised migrate across the older surfaces (Visser and Schoch, 1973). The fourth landscape type is the Langebaan Road Plain that can be found to the north and west of Langebaan Road. The landscape is a calcrete surface that lacks relief features and has an elevation of 35mamsl. The Berg River Valley that crosses the area from east to west forms the next landform. The river meanders in a broad valley with a floodplain that reach a width of 2 to 3 km at the river mouth. Tidal action is visible up to 25km inland. Isolated granite hills (“koppies”) form the last of the identified landforms and reach elevations of up to 300mamsl. These hills are scattered between Langebaan and Darling, formed in part by the Langebaan and Darling plutons. The Vredenburg headlands are also formed by granite intrusions. The Table Mountain sandstone forms an escarpment to the northeast of the study area and forms the highest point above sea level.

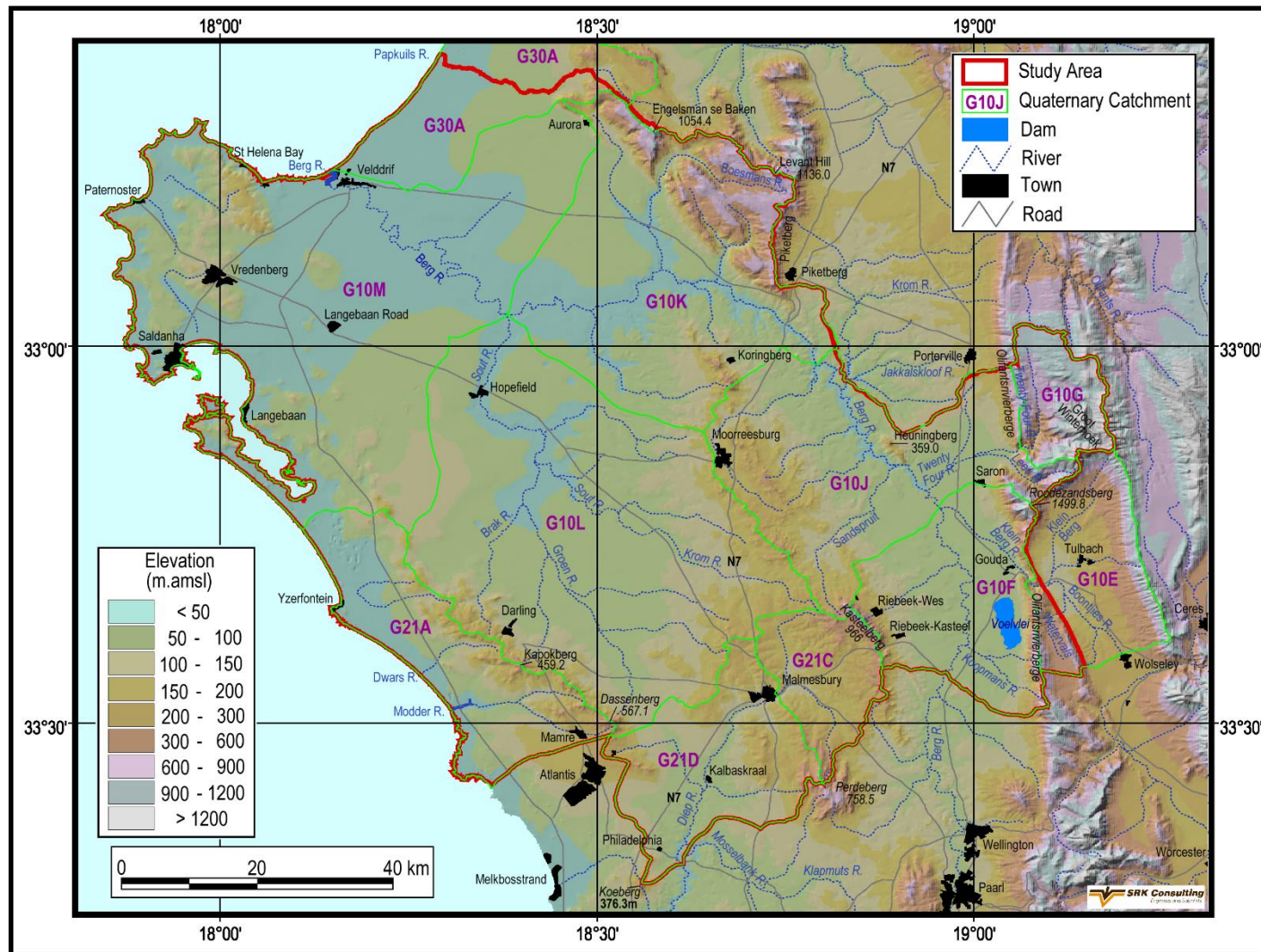


Figure 28: Physiography of Study Area (Woodford, et al., 2003).

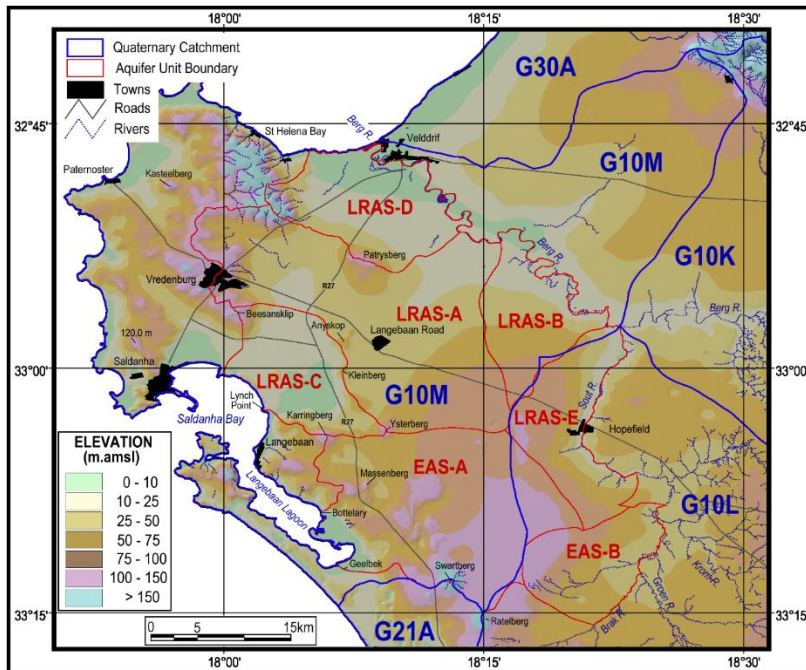


Figure 29: The topography of the northern part of the study area (Woodford and Fortuin, 2003).

3.5 Vegetation

Timmerman (1988) used the vegetation classification of Acocks (1975) to describe the vegetation and found only two vegetation types, namely the Strandveld that could be found along the entire beach front and in the floodplain of the river and Coastal Macchia that was found over the rest of the area. This classification excludes the vegetation that occurs on the Table Mountain Sandstone escarpment, as Timmerman (1988) did not include this area into his study. The Sandveld and the old dune areas kept their original shrubby character, as Port Jackson willows (*Acacia cyanophyllum*) and Rooikranz trees (*Acacia cyclops*) have replaced large parts of the natural flora (Timmerman, 1988). It is clear from Figure 30 that the vegetation changes with the varying climate and geomorphological settings going from Coastal Macchia and Fynbos along the coast to Renosterveld in the central and eastern sections of the study area (Low and Rebelo, 1996; Woodford, et al., 2003).

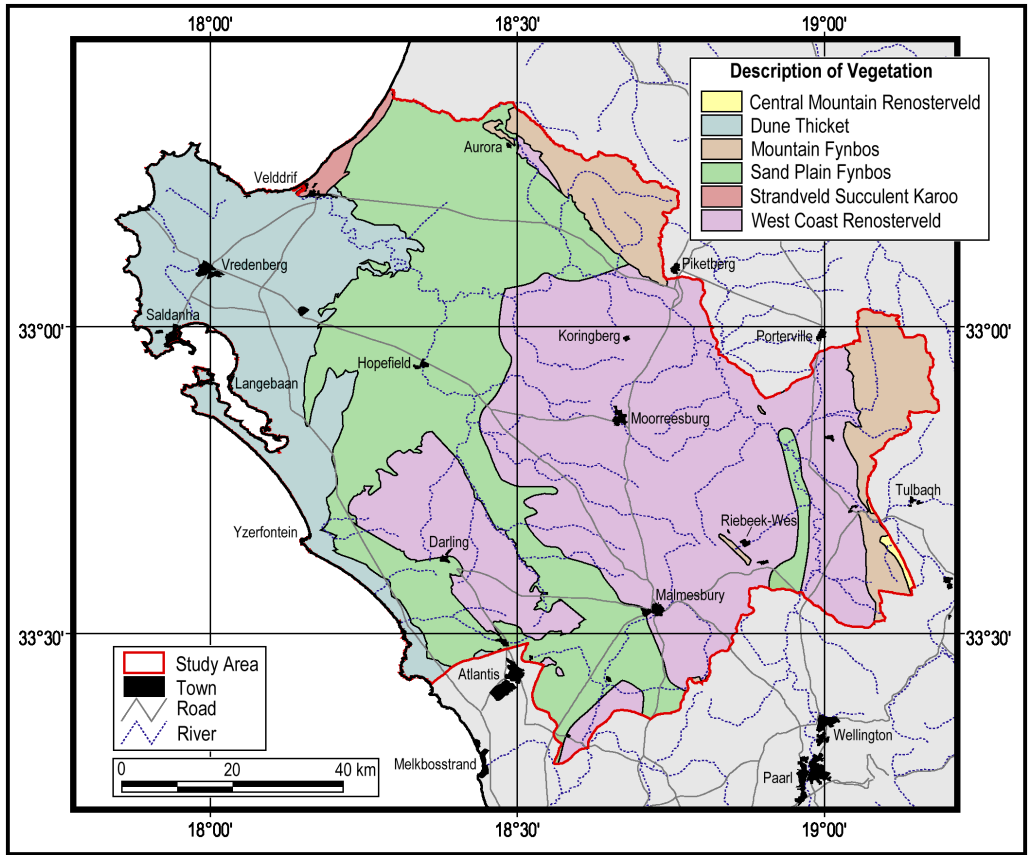


Figure 30: Vegetation Types of the Study Area (Woodford, et al., 2003; after Low and Rebelo, 1996).

3.6 Land-use

In the 1980s about 40% of the Sandveld vegetation have been cleared in strips for growing wheat in winter and the cultivation of vegetables in summer. Most of the agricultural activities had been limited to dryland farming, with a lack of large-scale irrigation. The reason for this was in part the prohibition on the abstraction of large volumes of water under the Saldanha Subterranean Government Water Control Area. Groundwater abstraction in the Langebaan Road Aquifer Unit was limited to domestic use and stock watering purposes (Timmerman, 1988). Potato farming has led to the clearance of larger stretches of land with pivot point irrigation taking the place of dryland farming to the north of the Berg River. Large parts of the Langebaan Road plain had been used for dairy farming (Timmerman, 1988), but this has change in recent years. The economic potential of the area lies in mining (minerals such as limestone, kaolin, phosphate, gypsum, glass sand and construction materials) (Noble, 1976), industrial development, agriculture and tourism. Water availability is a constraining factor. Figure 31 provides information on land use in the area (DWAf, 2008).

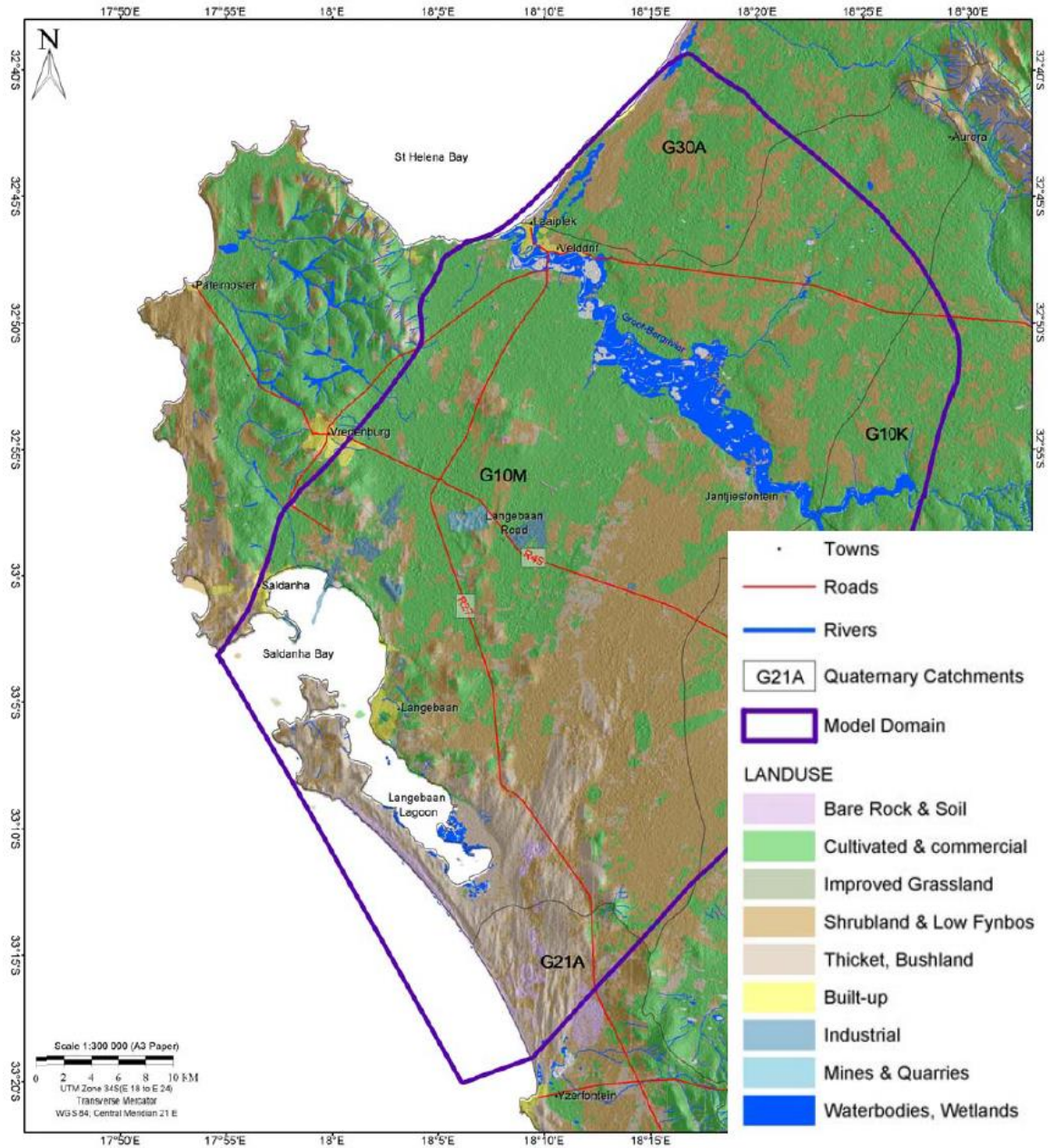


Figure 31: Land Use of the area (DWAf, 2008).

3.7 Geology

The geology of the study area is very important as it is the driver of the groundwater system. It is more important than surface topography in determining the geohydrological behavior of the area that is covered with Tertiary and Quaternary sands which is mostly unconsolidated with semi-consolidated dune sands in areas (Noble, 1976) and calcrete. The basement topography (palaeochannels), faults, fissures, contact zones and the stratigraphy of the Cenozoic deposits all contribute to the complexity of the groundwater recharge, flow and discharge of the Lower Berg

River Aquifer System. The basement is formed by Malmesbury Group shales and granites from the Cape Granite Suite. Granite outcrops occur in a number of places, with granite underlying the tertiary layers in the west. Malmesbury shale is mostly the underlying formation found towards the east.

Fine to very fine-grained sand forms the tertiary sediments, with silt and peat layers in places. Layers of calcrete, clay and poorly sorted gravel are also found (Vegter, et al., 1976). The calcrete layers occur mostly near the surface, but is not persistent (Noble, 1976).

The sediments in the area were deposited in a geosyncline that is steeply folded along a northwest striking axis (see Figure 32) (Visser, 1989). It occurs in three tectono-stratigraphic domains (Visser, 1998) that is separated by two major north-northwester trending fault systems, i.e., the Franschhoek-Saldanha (Colenso) Fault System and the Wellington-Piketberg Fault System. Accretion – gradual accumulation of additional layers - was thought to have occurred during the main episode of the Pan-African collisional tectonics (Kisters, et al., 2002).

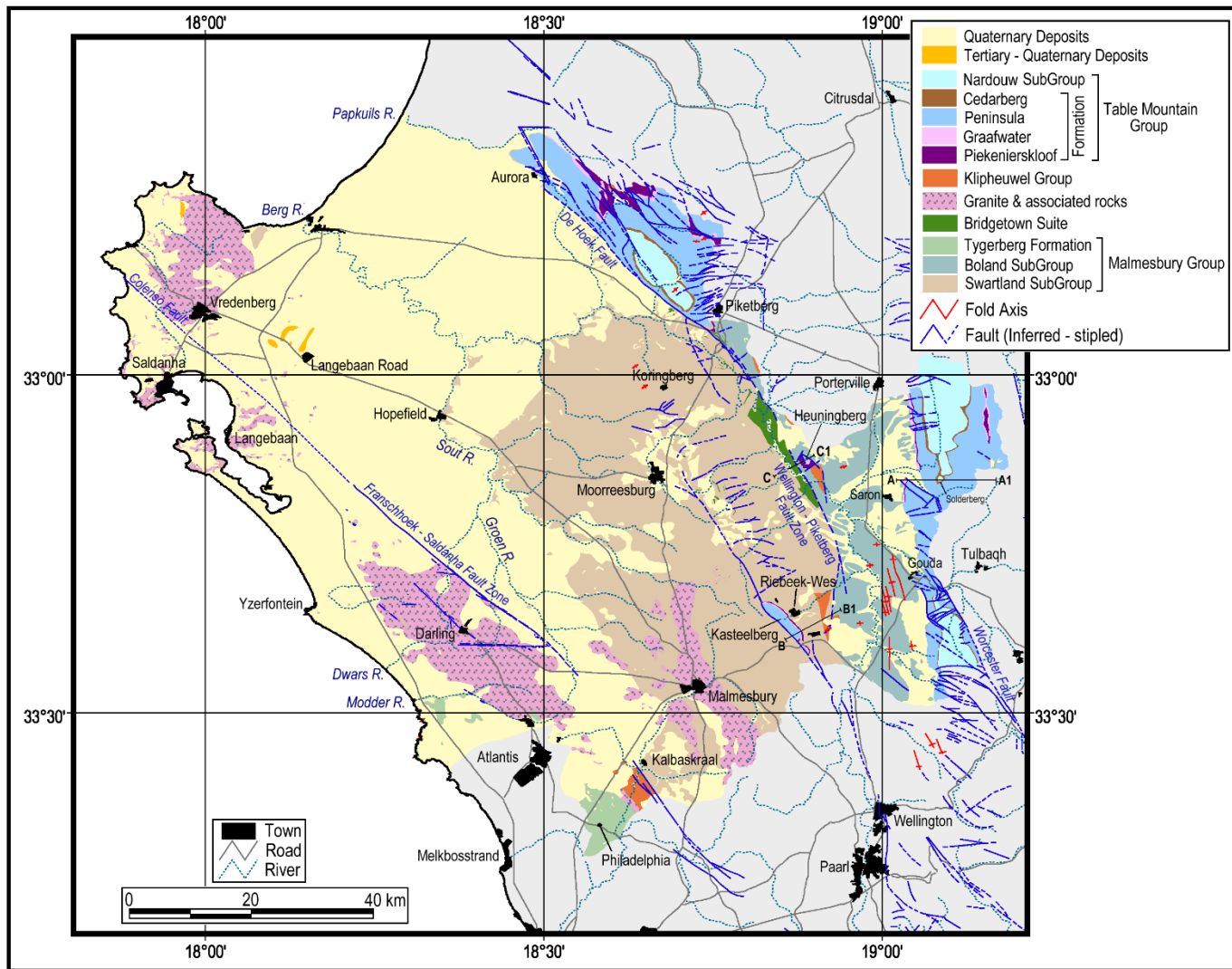


Figure 32: Geology of the Study Area (Woodford, et al., 2003).

The inferred contact between the granites in the western part and the Malmesbury formation in the eastern part of the study area coincides with a major fault zone, known as the Colenso Fault (Timmerman, 1985a) as can be seen in Figure 33.

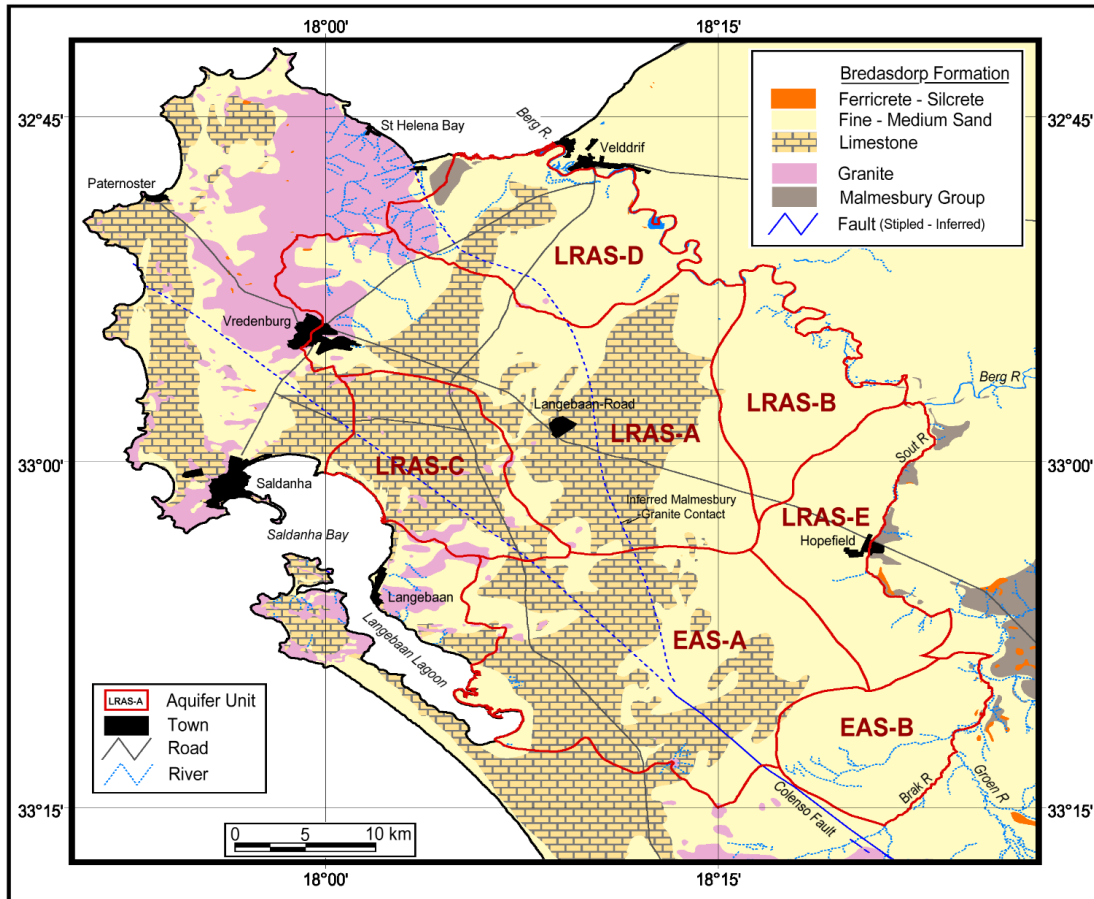


Figure 33: Simplified surface geology of the study area (Woodford and Fortuin, 2003).

3.7.1 Basement

The basement of the primary aquifer in the Lower Berg River region is formed by the following stratigraphic units:

- Malmesbury Group (late Cambrium);
- Cape Granite Suite (late Precambrium to early Cambrium);
- Cape Super Group (Ordovicium to Carboniferous).

The last group is only represented by the escarpment above Aurora, of which a small portion is included in the study area.

3.7.1.1 The Malmesbury Group

The Malmesbury Group could be described as a geosynclinal succession of sedimentary and low-grade metamorphic rocks of marine origin, but knowledge of

the group is limited. The reason for this is the generally poor exposure of the group, lithological discontinuity, intense deformation of some contact zones and metamorphism. It is thus not possible to determine whether certain boundaries are stratigraphic or tectonic. No correlation exists across the major faults within the Malmesbury Group and it is difficult to establish the thickness of the Malmesbury Group or any of its components with any certainty. It is assumed to have a total thickness of the Group would be more than 6km (SACS, 1980; Timmerman, 1988).

It is only the Tygerberg and Moorreesburg Formations that occur in the study area (See Figure 34). The two formations are very similar, except for some basal lavas and tuffs in the Tygerberg Formation. Younger formations cover the Malmesbury Group, which means that the Tygerberg Formation in the west and the Moorreesburg Formation in the east are not visible at surface. It would seem that the Malmesbury metasediment were deeply weathered during the early Cenozoic, which resulted in a sericitic clay. The clay may form a layer that can be 50m thick and is considered to be impermeable where it is present (Timmerman, 1988). This weathering also formed palaeochannels, in which the Cenozoic sediments were deposited.

3.7.1.2 Cape Granite Suite

The Malmesbury Group sediments were intruded by a series of late Precambrian to early Cambrian age granitic plutons (Figure 34), at anticlinal fold hinges. There is a strong alignment with the dominant northwest-southeast tectonic trend that developed during the Saldanian Orogeny (Woodford, et al., 2003). There are two major batholiths in the study area, the first being the Darling batholith that from the hills around Darling, while the second is the Saldanha-Langebaan batholith in the vicinity of Saldanha Bay (Timmerman, 1988) Roberts and Siegfried (2014) also includes the Vredenburg batholith as separate from the Saldanha-Langebaan batholith. The batholiths cover a roughly elliptical area (Schoch, 1972), with the long axes roughly parallel with the Colenso Fault System. The Colenso Fault acts as a boundary between the Saldanha and Vredenburg Batholiths. The Saldanha and Darling Batholiths occur to the south west of the fault Tygerberg Terrane, while the Vredenburg Batholith from part of the Swartland Terrane to the northeast (Roberts and Siegfried, 2014). There is a similarity in the mineralogy of the Darling and Saldanha batholiths. The younger granites of the Darling batholith are well-jointed with prominent horizontal joints, which appears like outliers of Table Mountain sandstone from a distance (Schoch, 1972).

The granites are widespread in the western part of the study area where the outcrops often form hills that dominate the dune landscape. These outcrops usually have a distinctive dome-like appearance as a result of exfoliation (Schoch, 1972). Cenozoic sediments cover the granite in several places. In these situations, the granite forms a weathered zone that may be several meters thick, consisting of a kaolinitic clay.

The clay layer is considered to be the base of the primary aquifer system, and seen to be impermeable (Timmerman, 1988).

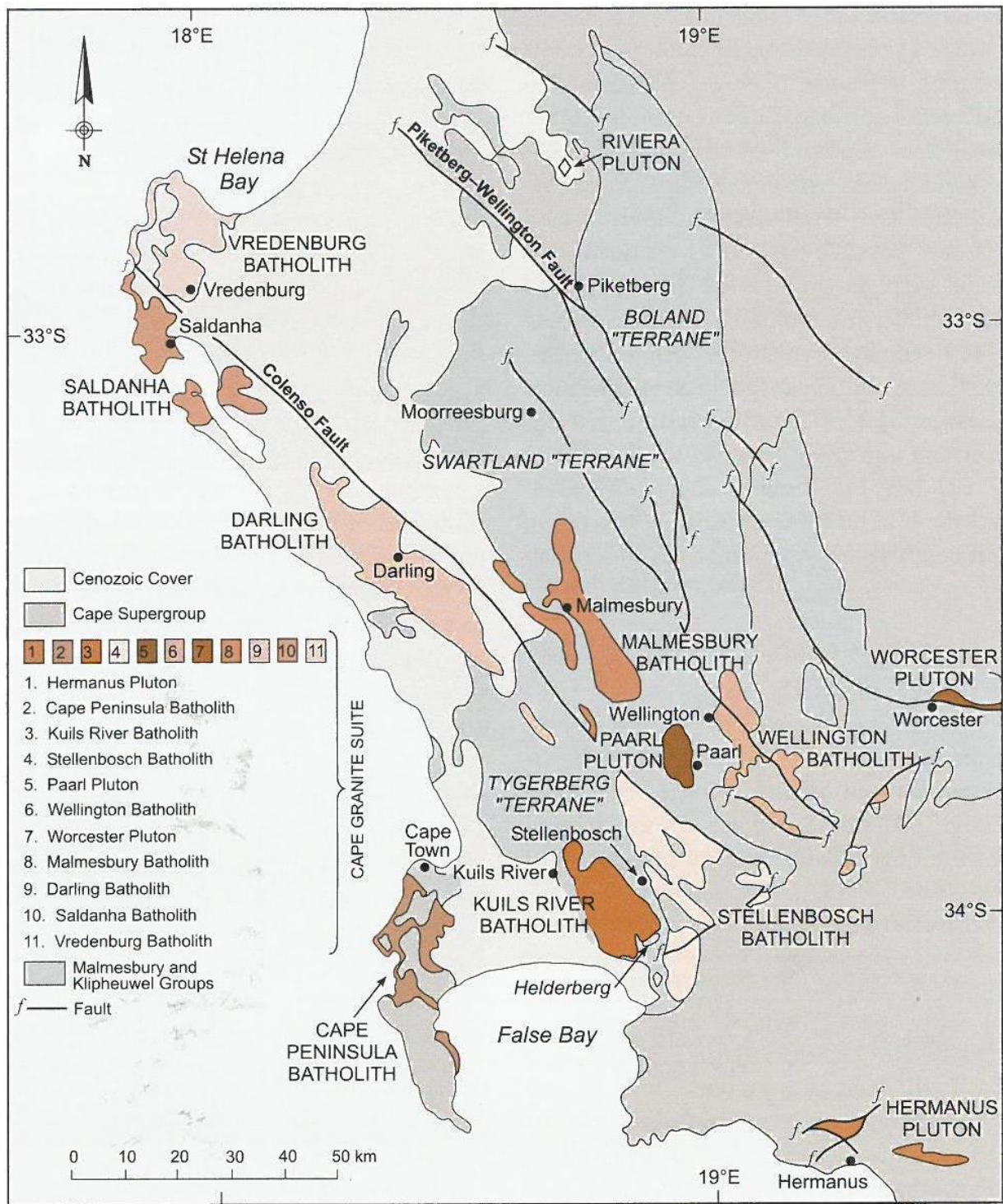


Figure 34: Geology of the Berg River catchment area showing the fault lines and granite plutons (Roberts, et al., 2006).

3.7.2 Cenozoic Deposits

Sediments in the area reaches a maximum thickness of more than 100m at Anyskop and at Elandsfontein Farm (see Figure 35), with an average thickness of around 70m (Woodford, et al., 2003; DWAF, 2008; Roberts and Siegfried, 2014). The greatest thickness is found in the palaeochannels that was cut into the Palaeogene landscape by rivers like the Berg River. It is believed that sea-levels were much lower than the present levels when the palaeochannels were formed. The palaeochannels will be discussed later, as they are pertinent to the understanding of the groundwater flow in this groundwater system. The gravels, sand, and clayey deposits of the Elandsfontyn, Saldanha and Varswater Formations were deposited during this time of sea-level transgressions and regressions. The overlying sediments were primarily aeolian sand and comprise the Springfontyn, Langebaan and Witzand Formations. These sediments were grouped together as the Cenozoic deposits, with the lithostratigraphy between Cape Town and Elands Bay described in detail by Rogers (1982). The extensive exploration drilling by Timmerman (1985a; b) added to our understanding of the coastal aquifer system and the description of the Cenozoic deposits in the area (Woodford, et al., 2003).

Indications are that the area experienced a subtropical to tropical climate during the Palaeogene, which led to deep weathering of the basement rocks. There is thick sericitic clay capping the Malmesbury deposits, with kaolinitic clay covering the Cape Granites. These were thought to originate from the weathering of the basement rocks. The coarse-grained Elandsfontyn sand and gravel were deposited in a number of high-energy, palaeo-rivers that were cut into the basement formations. This includes the old course of the Berg River and a few of the other rivers in the study area. It appears from the deeply incised palaeochannels that the sea-level during this time was up to 50m below the current mean sea-level (Timmerman, 1988). Coarse sand and gravel alternate with peat and clay layers were deposited as fluvial sediments in the floodplain and swamp environments of the system. The Varswater Formation was deposited subsequently during cycles of marine transgression and regression. This is followed by unconsolidated aeolian deposits that consists of reworked Varswater sediments. Timmerman (1985c) noted that the Varswater sediments do not extend further than 15km inland (Woodford, et al., 2003).

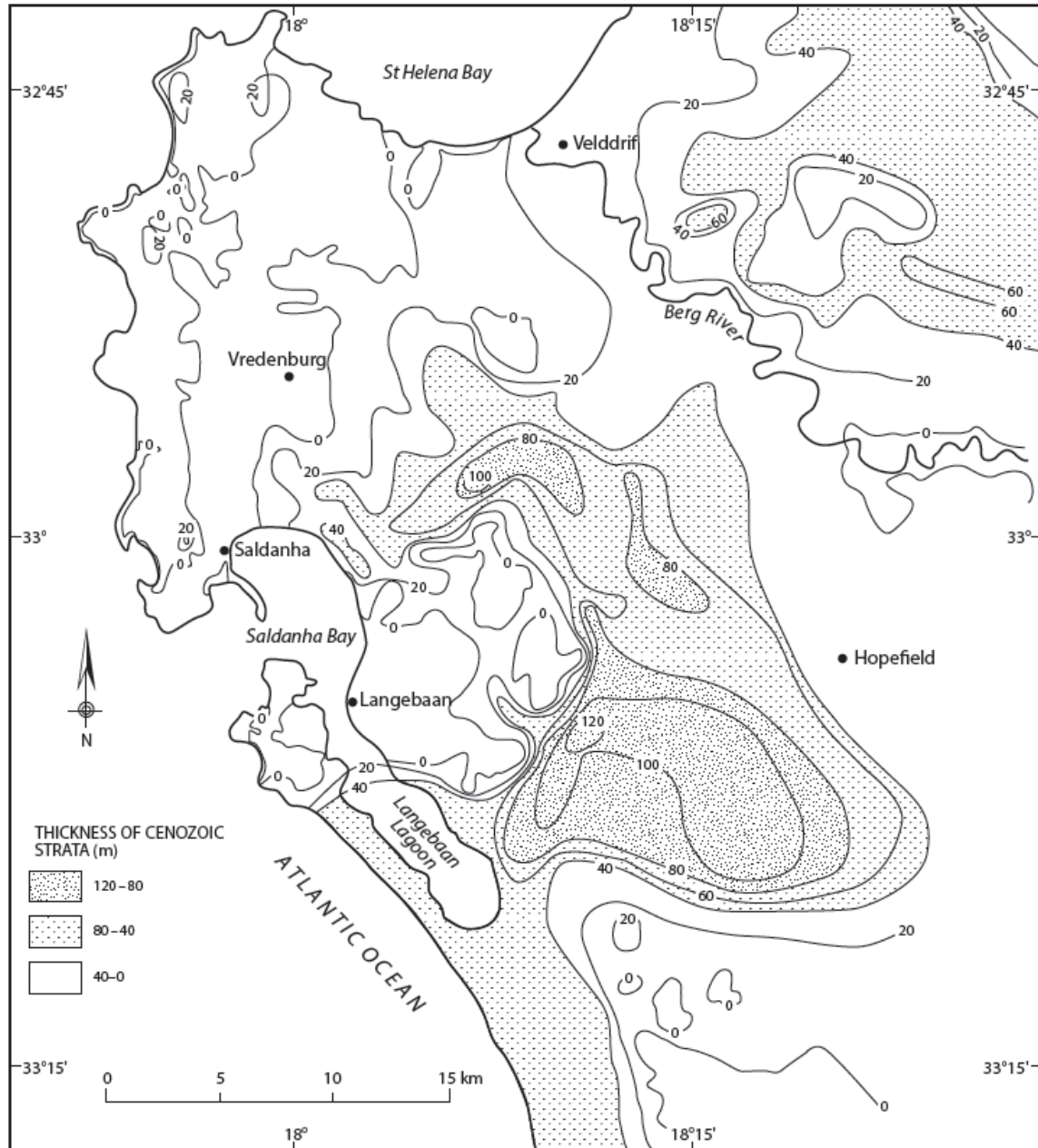


Figure 35: Isopachs of Cenozoic strata in the Saldanha, Vredenburg and Velddrif environs. The depocentres record the locations of ancient channels of the Berg River and possibly the Groen River in the east (Roberts & Siegfried, 2014).

3.7.2.1 Elandsfontyn Formation

These deep river channels were filled with a variety of sediments, mostly in fluvial circumstances, with coarse sands and gravels alternating with peat and clay layers (Timmerman, 1988; Woodford, et al., 2003). This means that the distribution of the Elandsfontyn Formation is largely determined by the palaeochannels, that it often occurs below sea level, reaching a maximum stratigraphical height of 5m amsl. The

maximum depth of the Elandsfontyn Formation is 50m below present sea level. The coarse materials are normally at the bottom of the sequence, while the peat and clay layers deposited near the top. It provides an indication that there were higher energy levels at the early stages of the fluvial deposits, with the river forming channel deposits and point bars. The later deposits most probably took place in flood plain and marshy conditions (Timmerman, 1988; Woodford, et al., 2003). These deposits are not well known, because of a lack of natural or artificial outcrops. They have only been described from a number of boreholes (Rogers, 1980; De la Cruz and Du Plessis, 1981; Rogers, 1982; Smith, 1982; Woodborne, 1982; Woodborne, 1983; Timmerman, 1988; Grindley, et al., 1989; Theron, et al., 1992; DWAF, 2008). Rogers (1980) proposed the name “Elandsfontyn Formation” for this layer. It should not be confused with Elandsfontein, which is used to describe the Elandsfontein aquifer unit.

The formation is characterized by cycles of angular, quartzose, gravelly sand fining upwards to cohesive, often peaty clays, as seen in the type borehole G30878 on Elandsfontyn 349, west of Hopefield (Figure 36). The environment in which the clays were deposited when deduced from lithological evidence and vegetation represented by pollen taxa were that of a tropical meandering river (Coetzee and Rogers, 1982; Theron, et al., 1992). Figure 37 show the Elandsfontyn Formation in borehole S1 in the Langebaan Road Aquifer in the context of the other deposits (Roberts and Siegfried, 2014).

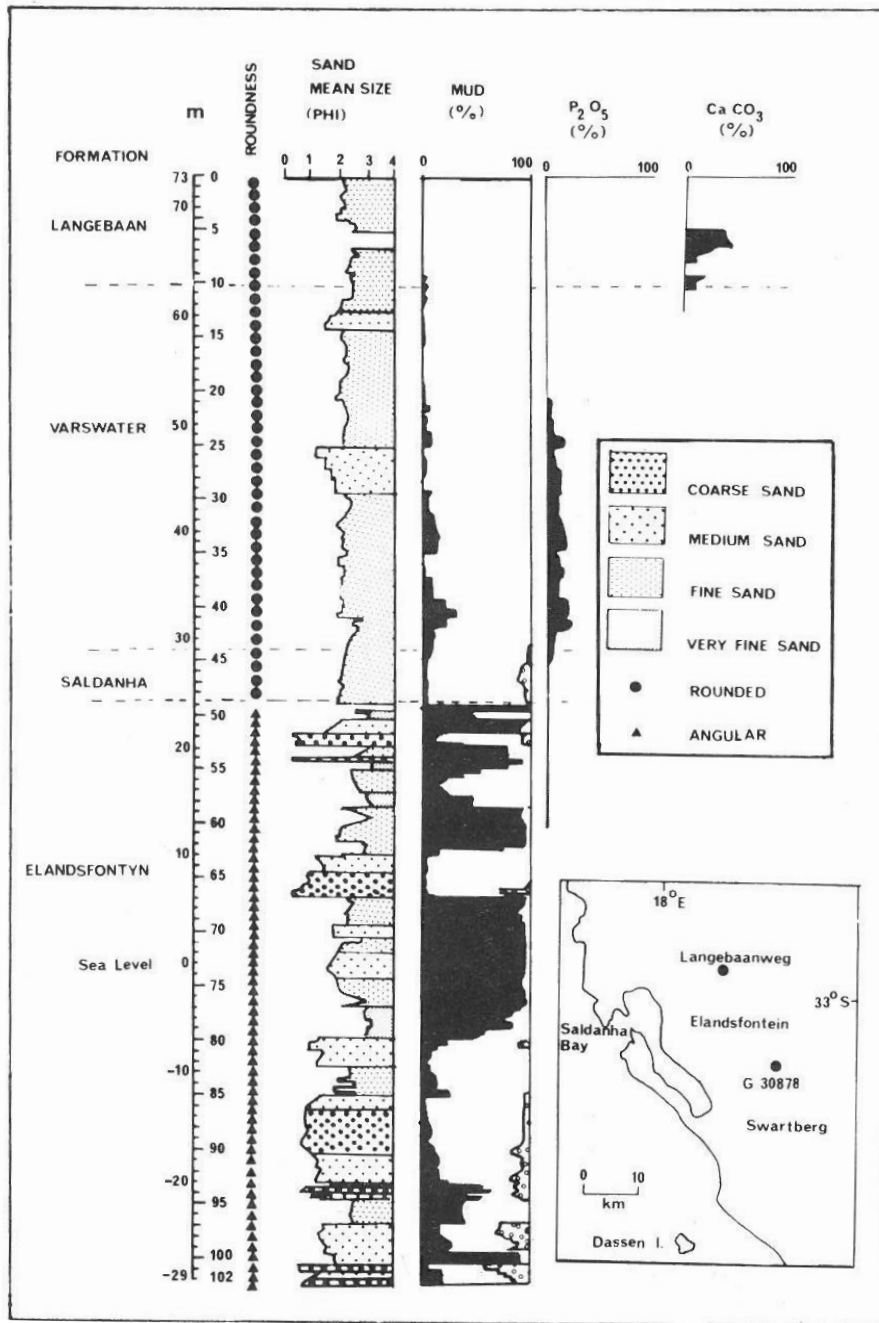


Figure 36: Stratigraphy of the Elandsfontyn Formation in borehole G30878 on the farm Elandsfontyn 349, west of Hopefield (after Rogers, 1980; Theron, 1992).

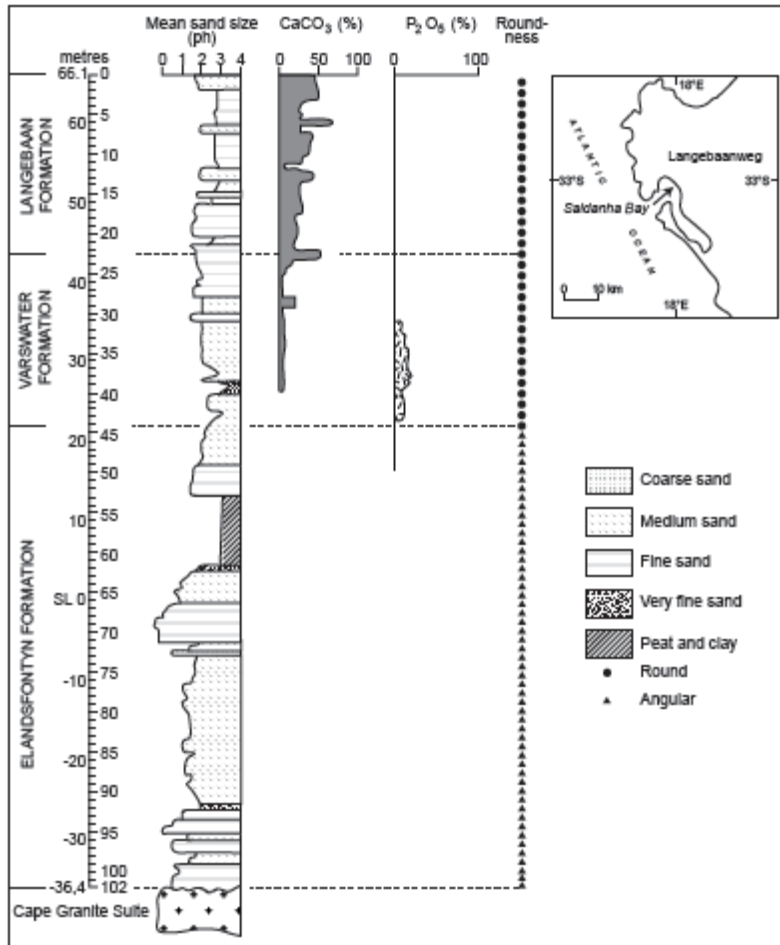


Figure 37: Stratigraphy and sedimentology of the fluvial Elandsfontyn Formation, shallow-marine Varswater Formation and aeolian Langebaan Formation in the S1 borehole (after Rogers; Roberts & Siegfried, 2014).

The Elandsfontyn Formation is continuous between the Berg River and links the two palaeochannels (Figure 38) as can be seen from the subsurface distribution. Borehole logs seem to indicate that the link between the two palaeochannels may be formed by the clay layer of the Elandsfontyn Formation, and that the sand unit may be absent (Timmerman, 1988; DWAF, 2008).

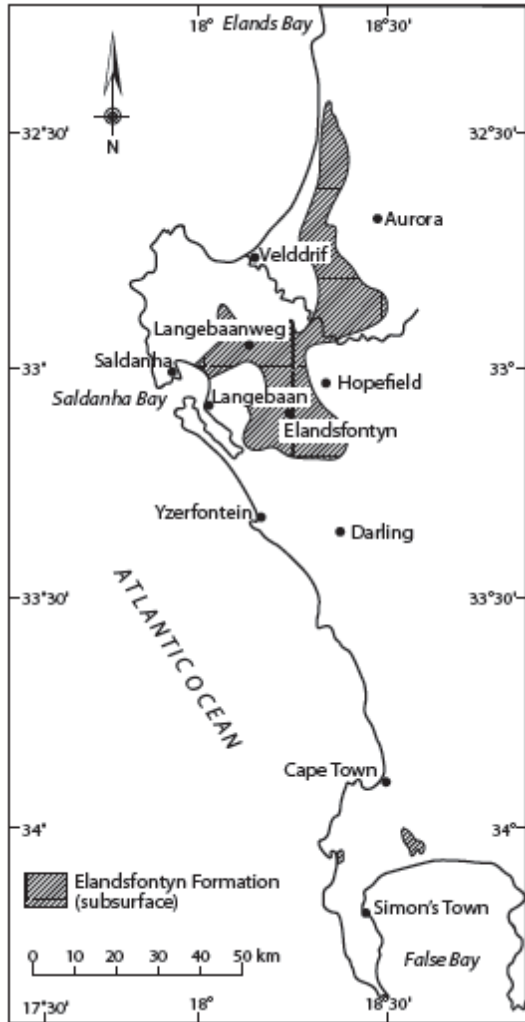


Figure 38: Subsurface distribution of the Elandsfontyn Formation in the Saldanha, Vredenburg and Velddrif environs. (Modified after Timmerman, 1988 and Cole and Roberts, 1996; Roberts & Siegfried, 2014).

3.7.2.2 Saldanha Formation

The Saldanha Formation is a controversial phosphatic quartzose sandstone layer, that is poorly exposed and not well documented (Timmerman, 1988). It was described by Tankard (1975a) as a consolidated conglomeratic phosphorite from occurrences on Hoedjiespunt Peninsula at Saldanha and the Varswater Quarry on Langeberg 188. The correlation of phosphatic exposures on Hoedjiespunt with the occurrence at the Varswater Quarry has since been rejected, due to lithologically dissimilarities (Birch, 1977; Dingle *et al.*, 1979; Rogers, 1980). It can probably correlate with the Varswater Formation. Timmerman (1988) could not find this layer in boreholes drilled during his investigation of the study area.

3.7.2.3 Varswater Formation

The type section of the Varswater Formation is in Varswater Quarry at Langebaanweg (Figure 39). Rogers (1982) had provisionally subdivided the formation into four members. The lithostratigraphy of the formation has since then been reviewed extensively (Dingle *et al.*, 1979, 1983; Hendey, 1983; Rogers, 1983). The formation consists of deposits of phosphatic sand, which was exploited by Samancor, later Chemfos (now owned by BHP Billiton). It became known internationally for its rich Pliocene assemblage of vertebrate fossils (Hendey, 1981a, and 1981b).

Timmerman (1988) mapped the distribution of Varswater Formation (see Figure 40) in the northern part of the map area and found that the marine deposit was restricted to western, i.e., seaward parts of major bedrock depression east of Langebaan Lagoon and Saldanha Bay (Theron, *et al.*, 1992). The Varswater Formation does not extend further than 15km inland (Timmerman, 1988; Woodford, *et al.*, 2003). In boreholes the Varswater Formation can be distinguished from underlying deposits by rounded quartz grains. This is in sharp contrast with very angular grains in the Elandsfontyn Formation. The presence of phosphate is an additional characteristic of Varswater Formation that is absent from the Elandsfontyn Formation. There is, however, an upper boundary level above which the phosphate is absent (Theron, *et al.*, 1992). Figure 40 shows the distribution of the Varswater Formation (Roberts and Siegfried, 2014). The Varswater Formation is absent from the south-eastern part of the Grootwater aquifer unit, but it can reach a thickness of more than 30m on the farms Grootwater, Tijgerfontein and Rondeberg (Timmerman, 1985a).

(i) *Langeenheid (Shelly Gravel) Member*

These deposits consist basically of gravels with phosphatized shell fragments, rolled phosphatic sandstones, pellets and rolled pebbles of bedrock material. It is only found locally, with its the components often embedded in muddy, sandy material. It is possible that the shelly gravel deposits are the result of the first erosion phase of the Varswater transgression and subsequent sedimentation in a high energy beach and inner shelf environment (Rogers, 1980, and 1982; Timmerman, 1988).

(ii) *Konings Vlei (Quartzose Sand) Member*

Large vertebrate fossils of early Pliocene age (Hendey, 1981) are found in the quartzose sand that is interbedded with lenses of intertidal clay, peat and even river channel sediments (Dingle, *et al.*, 1979). Rogers (1982) describes these sediments as being deposited in an estuarine environment where Pliocene rivers, possibly the proto-Berg River, meandered through the floodplain.

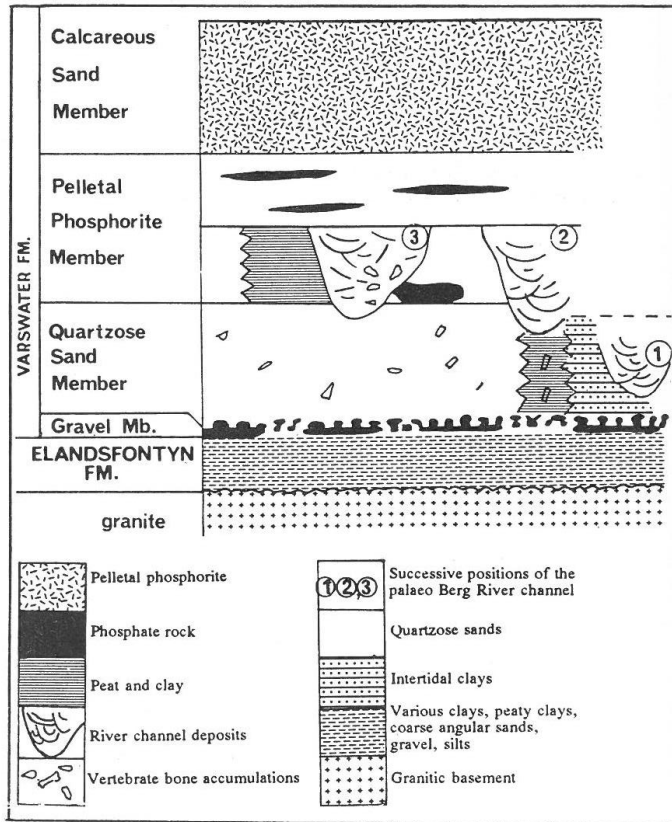


Figure 39: Lateral lithofacies relationship in the Varswater Formation as exposed in the New Quarry, Varswater (adapted from Dingle *et al.*, 1983 and Hendey, 1981b; Theron, 1992).

(iii) *Muishond Fontein pelletal phosphorite (Pelletal Phosphorite) Member*

The main component of the Varswater Formation consists of fine to very fine sand that is often silty or even clayey. The member is rich in phosphorite pellets and phosphatized shell fragments with levels high enough in areas to make it economically viable to mine. This formation has been deposited in an intertidal lagoonal to inner shelf setting (Rogers, 1982). It is possible that the Pliocene transgression had reached its highest point with a number of lagoons and embayments forming along the Cape Coast. Guano that was deposited on nearby granitic islands is the possible source of the phosphate deposits (Rogers, 1980; Timmerman, 1988).



Figure 40: Subsurface distribution of the Varswater Formation (Roberts, 2006b; Roberts and Siegfried, 2014).

(iv) *Langeberg quartz sand (Calcareous Sand) Member*

This layer consists of calcareous sand poor in phosphate with intercalated calcretes (Hendy, 1981). According to Rogers (1982) these calcareous sands were Pliocene mid-shelf deposits (Timmerman, 1988).

3.7.2.4 Silwerstroom Formation

The Silwerstroom sediments emit a similar gamma count as the Elandsfontyn sediments but can be differentiated based on the roundness of the particles and the shell content (Timmerman, 1985a).

3.7.2.5 Springfontyn Formation

The Springfontyn Member consist of cohesionless bodies of medium quartzose sands with a granulometric size distribution that is identical to that of the overlying dune sands. Rogers (1980) concluded that these sands were aeolian in origin and could be dated as late to middle Pleistocene. The original calcareous shelly sands have been leached, leaving layers of pure silica sands (Timmerman, 1988). At

Grootwater the Springfontyn Formation is separated from the Varswater Formation by an intermittent muddy sand horizon, called the Duynefontein Member (Timmerman, 1985a).

The Noordhoek Member consist of fine peaty quartzose sands that probably originate from backshore dune landscape. The Papkuils Member was probably deposited in a backshore lagoon consisting of muddy fine sands. Both these sediments are of a similar age as the Springfontyn Member but occurs further inland (Timmerman, 1988).

Varying amounts of organic fines are found inland in the Springfontyn Formation, while shallow (1 – 2m) unconsolidated sand, that is regarded as part of the formation occurs still further inland. This covers large areas west of the Berg River and is largely derived from nearby granite masses. The sediments also contain quartz and some feldspar. Where the sand changes colour to a reddish-brown it gives an indication of a fair percentage of iron (Theron, et al., 1992).

3.7.2.6 Noordhoek Formation

This sediment consists of fine, peaty quartzose sands. It is possible that it originated from a backshore dune landscape, where there was a substantial amount of dune pans (Timmerman, 1988).

3.7.2.8 Velddrif Formation

The Velddrif Formation was the result of the Eemian transgression that reached a level of 7m above the present sea-levels, that resulted in shelly and gravelly deposits locally along the coast and in the Berg River estuary (Rogers, 1980 & 1982; Timmerman, 1988). The type section of this formation was found close to Berg River mouth (Tankard, 1979), and it is also found south of the 33^o latitude where the Velddrif Formation is exposed below Malgaskop, south of Saldanha, and at various localities along Postberg Peninsula. There are other occurrences to the south such as south of Modder River on diorite outcrops, but they are too small to be shown on a map (Rogers, 1980, 1982). The Velddrif Formation includes consolidated lime-rich beds of shell, comminuted shell-coquina to clay and sand with shell layers. It can be found along the western shore of the Langebaan Lagoon, where it underlies the Langebaan Formation (Timmerman, 1988).

3.7.2.9 Langebaan Formation

This deposit of calcretes and limestone is mainly of aeolian origin and locally extend below sea-level were it covers large areas of the coastal plain. One of the markers for this layer is the shells of *Trigonephrus globulus*. It is believed that the extensive dune fields were formed during the Weichselian regression and were calcretized afterwards (Rogers, 1980; Rogers, 1982; Timmerman, 1988). The limestones (calcarenes) of the Langebaan formation overlies a variety of older units and are

found from sea level to altitudes greater than 200m. There are two distinct generations of dunes that are superimposed upon one another, with the older dunes heavily calcretized. The younger dunes can be found along the western shore of Langebaan Lagoon. Here the calcrete-capped, consolidated barrier dunes are exposed. The same kind of calcretised parabolic dunes extends from Yzerfontein in the south to the farm Elandsfontein. These dunes occur parallel to the younger dunes of the Witzand Formation to the west (Roberts and Siegfried, 2014). It is originally called the Langebaan Limestone Member (Visser and Schoch, 1973).

Langebaan limestone are usually medium grained and is slightly greyish to cream in colour. Comminuted shell and quartz grains can be clearly seen. There is a degree of cementation and hardness that varies in the formation (Roberts and Siegfried, 2014). The formation varies in thickness up to 88m (Visser and Schoch, 1973; Rogers, 1980; Rogers, 1982).

3.7.2 10 Witzand and Yzerfontein Formations

The Witzand Formation is the youngest of the Cenozoic deposits that can be found on the coastal plain and is formed by unconsolidated calcareous dune sands (see Figure 41). Timmerman (1988, based on Rogers, 1982) classifies it into two geomorphological dune types:

1. Active masses of Barchanoid dunes that moved inland from the beaches that was unsheltered from the prevailing south to south-easterly winds. Inland these sands become rapidly vegetated and may become partially cemented. It forms parabolic dune ridges that run parallel with the prevailing wind and are more abundant inland. Rogers (1982) named it the Witzand Member, now known as the Witzand Formation (Theron, et al. 1992).
2. Along the coast barrier dunes are found. These are quite distinct from the Witzand dunes and was named the Yzerfontein Member. The barrier dunes are at their greatest height north of Yzerfontein, attaining a height of 30m (Rogers, 1982; Timmerman, 1988).

Light-coloured, calcareous, coastal dune sand – recognized separately from underlying consolidated Langebaan Formation. Holocene deposits, named after the calcareous dunes on Witzand 2, northeast of Melkbosstrand (Rogers, 1980, 1982); product of sand deflation from modern beaches. In type area plume of unvegetated barchan dunes, as well as associated slightly vegetated parabolic dunes, extend inland from Duynefontyn towards Mamre and Atlantis.

Although younger dunes – separate, integral part of same dynamic system which formed older calcretised dunes of Langebaan Formation. Active masses of barchans megadunes moved inland from beaches that were not backed by cliffs and were exposed to southerly summer gales. In their wake these barchan dunes leave parallel

ridges of sand which may be vegetated and partially cemented. Both phases lithologically identical, varying from fine- to coarse-grained sand with fairly high percentage of shell fragments (25 - 60 per cent CaCO_3). Witzand Formation also present as barrier dunes north and south of Yzerfontein, adjacent to Table Bay, and along shores of False Bay.

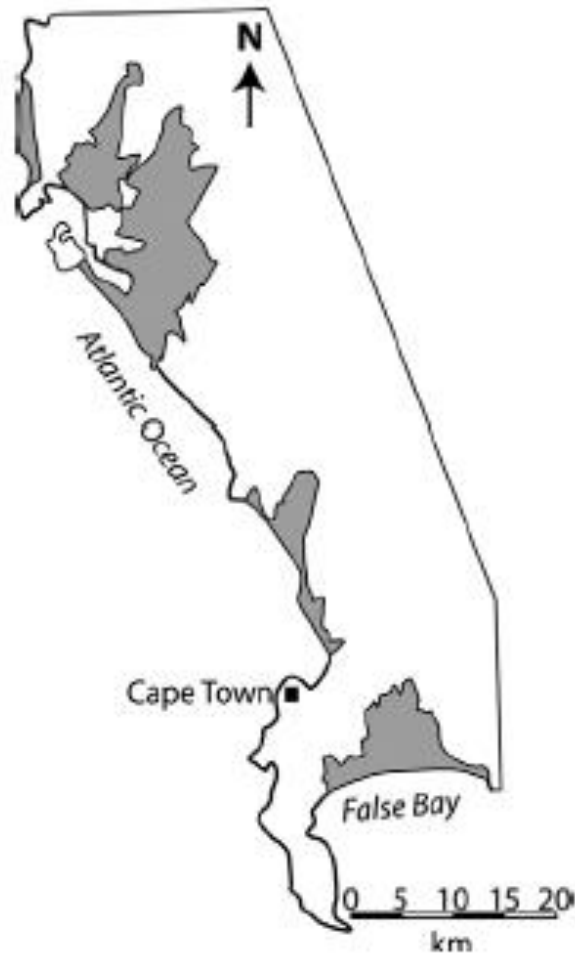


Figure 41: Dune field morphology along the lower west coast (modified from Geological Survey of South Africa, 1990). The exclusive development of dune plumes, whose orientation reflects the south-southwesterly dune building wind is clearly apparent (Roberts, et al., 2009).

3.7.2.11 Other Cenozoic deposits

Silcrete and Ferricrete occurs widely in the area, but it is difficult to map due to its small footprint. It occurs separately in many places, but there are also sites where they merge laterally or are intimately mixed. They are formed near the surface by groundwater concentrating iron oxide and/or silica that is derived from the underlying weathered rocks (Theron, et al., 1992). These layers can ultimately have an effect on the recharge of the aquifers.

Table 10 show the correlation between the different lithostratigraphic layers between the different aquifer units, while Table 9 gives the generalized geology of the study area. The names used in the original reports (K.M.G. Timmerman; Timmerman, 1985a; Timmerman, 1985b and Timmerman, 1988) were used, and where possible were linked with the latest designation.

Table 9: Generalized geological formations of the study area (Theron, *et al.*, 1992; Roberts and Siegfried, 2014).

	Age	Lithology & Genesis		Member		Formation	Group
Quaternary	Holocene	Biocalcareous-siliclastic sand (Aeolian)				Witzand	Sandveld
	Middle to Late Pleistocene	Biocalcareous-siliclastic sand (Aeolian)		Kraal Bay		Langebaan	
	Late Pleistocene	Biocalcareous-siliclastic sand (Aeolian)		Diazville			
	Middle Pleistocene to Holocene	Biocalcareous-siliclastic sand with intermittent peaty layers (Aeolian)				Springfontyn*	
	Middle to late Pleistocene	Shallow-marine coquina, sand and gravel, cemented to uncemented				Velddrif	
Neogene	Mio-Pliocene	Quartzose sand (Fluvial/estuarine)	Phosphatic sands, calcareous in part (Estuarine/tidal flat)	Langeberg quartz sand	Muishond Fontein pelletal phosphorite	Varswater	
	Late Miocene	Lightly cemented phosphorite gravel and boulders (marine)		Konings Vlei			
	Middle to Late Miocene	Greenish to reddish brown clayey sands (Estuarine)		Langeenheid			
	Middle to Late Miocene	Reddish biocalcareous sand (Aeolian) (Conglomeratic sandy phosphorite)				Prospect Hill (Saldanha)	
	Early to Middle Miocene	Gravel, sand, clay and peat (Fluvial)				Elandsfontyn	
Namibian / Cambrian	Granite, ignimbrites (Intrusive / Extrusive)				Cape Granite Suite		
Namibian	Quartzitic greywacke, mudrock and phyllite (Metaturbidites)				Tygerberg	Moorreesburg	Malmesbury

Table 10: Correlation of the lithostratigraphic layers of the different aquifer units, using information from (K.M.G. Timmerman; Timmerman, 1985a; Timmerman, 1985b and Timmerman, 1988).

Grootwater Aquifer Unit	Elandsfontein Aquifer Unit	Langebaan Road Aquifer Unit	Adamboerskraal Aquifer Unit
Yzerfontein Member	Witzand Formation (Witzand Member)	Witzand Formation (Witzand Member)	Yzerfontein Member
	Langebaan Formation (Langebaan Limestone Member)	Langebaan Formation (Langebaan Limestone Member)	
	Velddrift Formation (Velddrift Member)	Velddrift Formation (Velddrift Member)	Velddrift Formation (Velddrift Member)
Noordhoek Member	Springfontyn Formation (Springfontyn Member)	Springfontyn Formation (Springfontyn Member)	
	Calcareous Sand Member	Calcareous Sand Member	
Duynefontyn Member	Pelletal Phosphorite Member	Pelletal Phosphorite Member	
	Quartzose Sand Member	Quartzose Sand Member	
Silwerstroom Member	Shelly Gravel Member	Shelly Gravel Member	Bookram Member
	Saldanha Formation	Saldanha Formation	
Elandsfontyn Formation	Elandsfontyn Formation	Elandsfontyn Formation	Elandsfontyn Formation
Cape Granite Suite	Cape Granite Suite	Cape Granite Suite	Table Mountain Group
Malmesbury Group	Malmesbury Group	Malmesbury Group	Malmesbury Group

3.7.3 Palaeochannels and fault systems

3.7.3.1 Palaeochannels

Efforts to accurately map the basement contours of the palaeochannels of the Lower Berg River Aquifer System have met with various levels of success. Figure 42 shows the latest version of the palaeochannel map (Roberts and Siegfried, 2014), with the coloured section indicating the section of the palaeochannels that is below sea level. One of the big challenges is that most geophysical methods do not work very well in these thick sedimentary deposits, and it is difficult to differentiate between

weathered bedrock and the Cenozoic deposits itself. Timmerman (1988) has also assumed that there would be a thick layer of sericitic or kaolinitic clay covering the base of the palaeochannel, which adds to the difficulties. Recent drilling has already indicated that this latest version of the basement topography may have a number of flaws (Nel, 2019). The fact that it indicates the links between the Adamboerskraal, Langebaan Road and Elandsfontein aquifer units, and hints at a link with the Grootwater aquifer unit (which is to the south outside of the map) is already providing a model that correlates with observations in the field, as well as monitoring data. This palaeochannel map was used by Seyler, et al. (2016) in the development of a flow model for the area. This model will be discussed in Chapter 6.

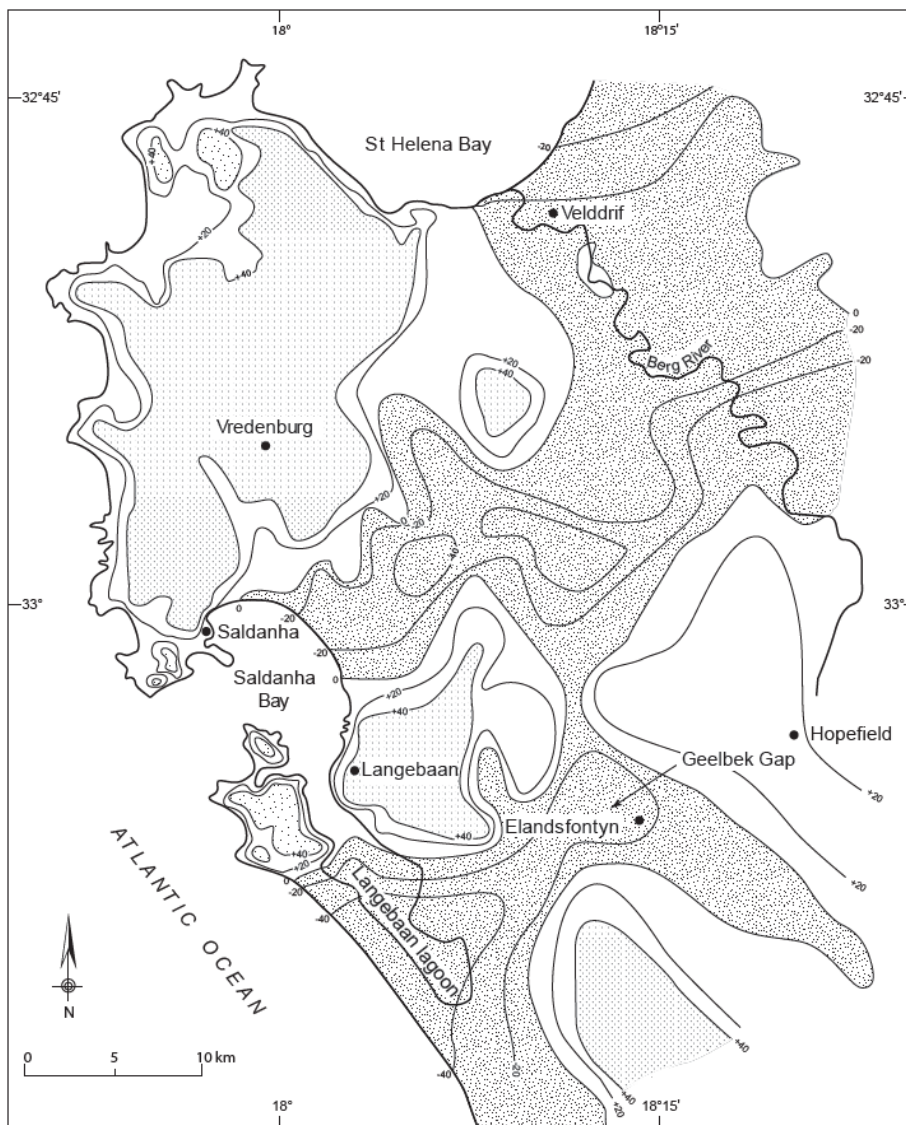


Figure 42: Palaeochannel map of the Lower Berg River Valley aquifer system, showing basement contours (Roberts and Siegfried, 2014).

Roberts, et al. (2017) modeled the conditions that could have contributed to the deposition of the Elandsfontyn Formation. The results are given in Figure 43, which provides changes in sea level and thus the potential impact it may have had on the deposition patterns, while Figure 44, provides an indication of the deposition of the Elandsfontyn Formation, which was deposited in the deepest parts of the Berg River palaeochannel. Figure 43A shows the exposure DEM surface, with the modern coastline, while Figure 43B provides a coastal configuration of the area during the Early/Middle Oligocene, when the sea level was 40m lower than the present sea level. Figure 43C shows the -20m sea level that was associated with the warming during the Late Oligocene and the intermediate levels during the early Miocene, when the site of borehole SBQW_{4/23} was associated with a stranded lake. Figure 43D represents the early/middle Miocene when the sea level was +5m above the present sea level. The light blue lines indicate the most likely position of the palaeo-Berg River. Indications from the model results are that the flow of the proto-Berg River from the Langebaan Road embayment to the Geelbek embayment was quite large at times, which seems to indicate a very definite link between the two palaeochannels.

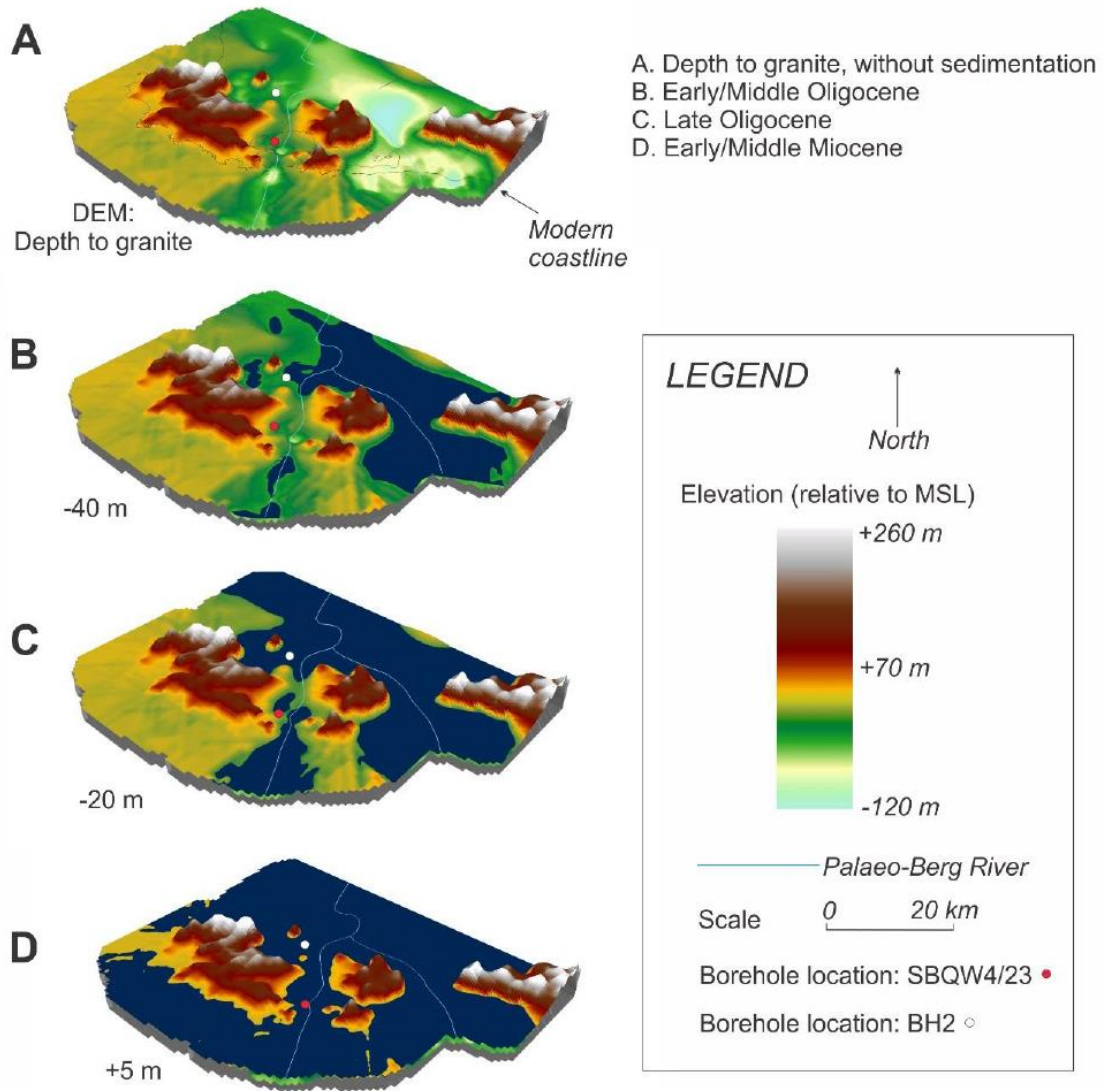


Figure 43: Modelled surface, shown as depth to granite, prior to deposition of the Sandveld Group (Roberts, et al., 2017).

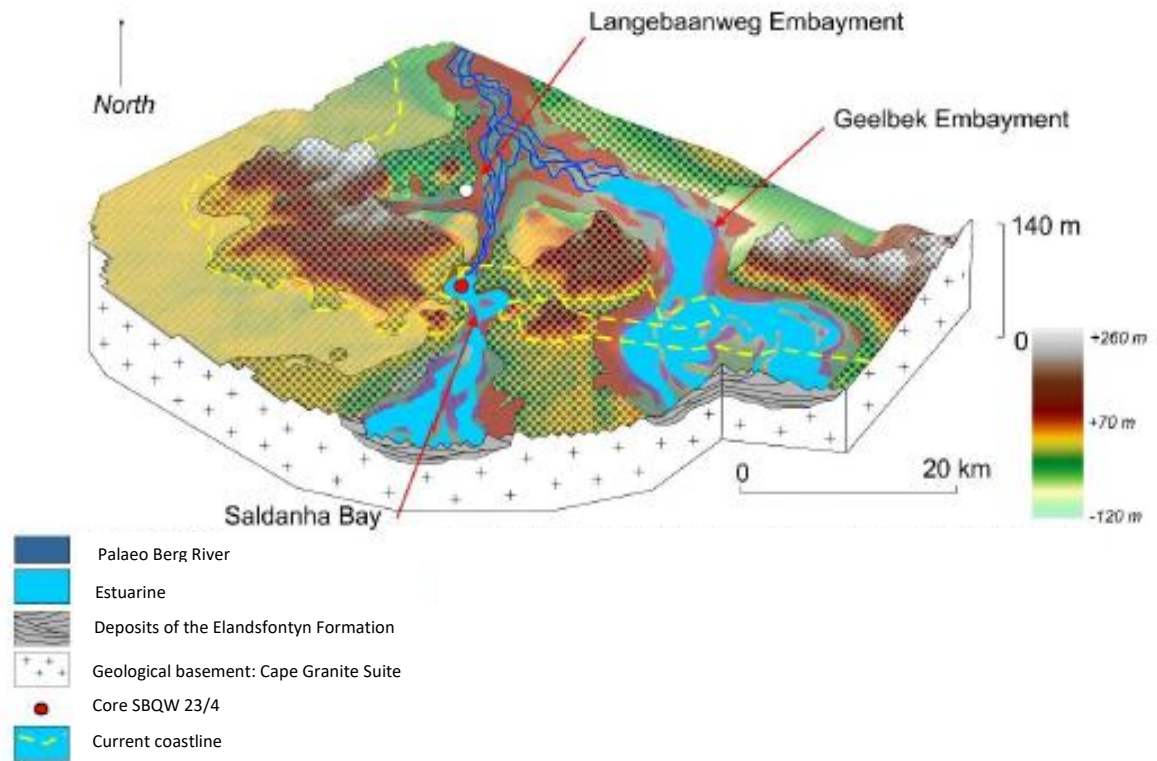


Figure 44: Schematic synthesis for Saldanha Bay during deposition of the Elandsfontyn Formation (Roberts, et al., 2017).

3.7.3.2 Fault systems

Geology maps or cross-sections often show faults as a single, solid lines. Faults are almost always more complex in nature and are usually made up of branching and coalescing splays or strands that form a much wider fault zone with an internal complexity (see Figure 45). The damage zone is much wider than the fault core, as shown in Figure 45A. Figure 45B shows (1) the branching-and-coalescing (anastomosing) geometry of the fault splays and (2) the formation of fracture geometries end breccia (broken) zones, so-called cataclasites, around the fault core. Figure 46 provides a simplified surface view of a fault zone. Fault zones are typically made up of branching and coalescing splays or strands that combine to form internally complex and thus a much wider fault zone (Kisters, 2018).

The definition given in the Dictionary of Earth Science for a fault zone is “A region, from metres to kilometres in width, which is bounded by major faults within which subordinate faults may be arranged variably or systematically. Single fault zones are marked by fault gouge, breccias and mylonites.” (Allaby, 2008). Each and every fault splay are also surrounded by a damage or process zone, where the rocks adjacent to the fault core have been broken up and fractured. The fault core may have a width

of meters up to tens of meters, compared to the width of the damage zone that may be ten to hundred times the width of the core. When faulting occurs near the surface (within the upper 1 – 3 km of the earth’s surface) it results in intense crushing and milling of the rocks. This produces gouge (clay-rich fault rock), breccias or cataclasites (broken and finely crushed rock). Surface of crustal water with dissolved minerals (quartz (SiO₂); carbonates ((Ca, Mg, Fe) CO₃); calcite and other carbonate minerals) may enter and permeate the fault core. The precipitation of these minerals will lead to the formation of quartz and/or carbonate veins, that are more resilient to weathering. The result is that it will form linear ridges in deeply weathered regions, making it possible to trace the fault core at surface (Kisters, 2018).

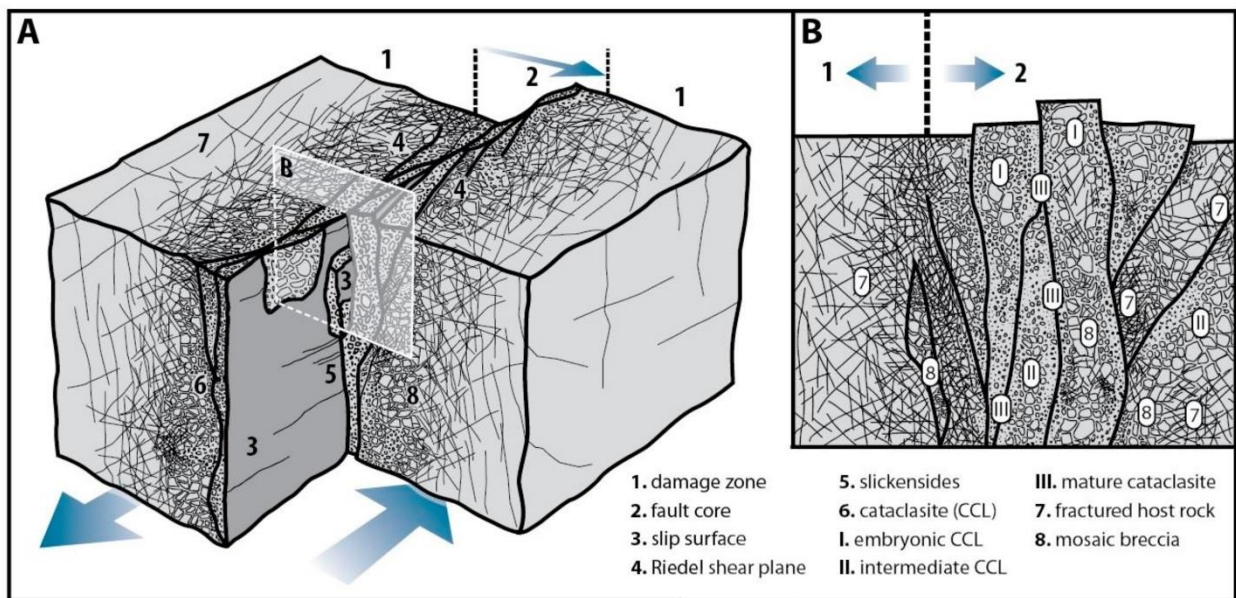


Figure 45: A. Schematic block-diagram through a brittle fault zone showing the development of a damage zone around the fault core. B. Cross-section through the fault (from Schröckenfuchs, et al, 2015; Kisters, 2018)

Faults are one of the most important geological structures that has the potential of controlling the occurrence of groundwater. One of the reasons for this is that it has a unique fabric that differs from the country rock. Fault zones often become the key locality for the exploration and exploitation of groundwater in hard rock terrains because it tends to consist of a highly fractured system (damage zone – see Figure 46) with dense secondary porosity when compared to country rock (Lin, et al., 2015). Gudmundssen (2000) provided two more reasons why fault systems affect the hydrogeology of the area in which it occurs. The damage zone of a fault system is often more prone to weathering, leading to the formation of valleys. Groundwater flows tend to follow the topography in unconfined systems, which could cause groundwater flow towards the fault system. The second reason would be that the

concentration of stress and fault slip maintains a relatively high permeability in active faults and its surroundings. Springs, especially hot springs, can be associated with active faults (Curewitz and Karson, 1997; Gudmundssen, 2000).

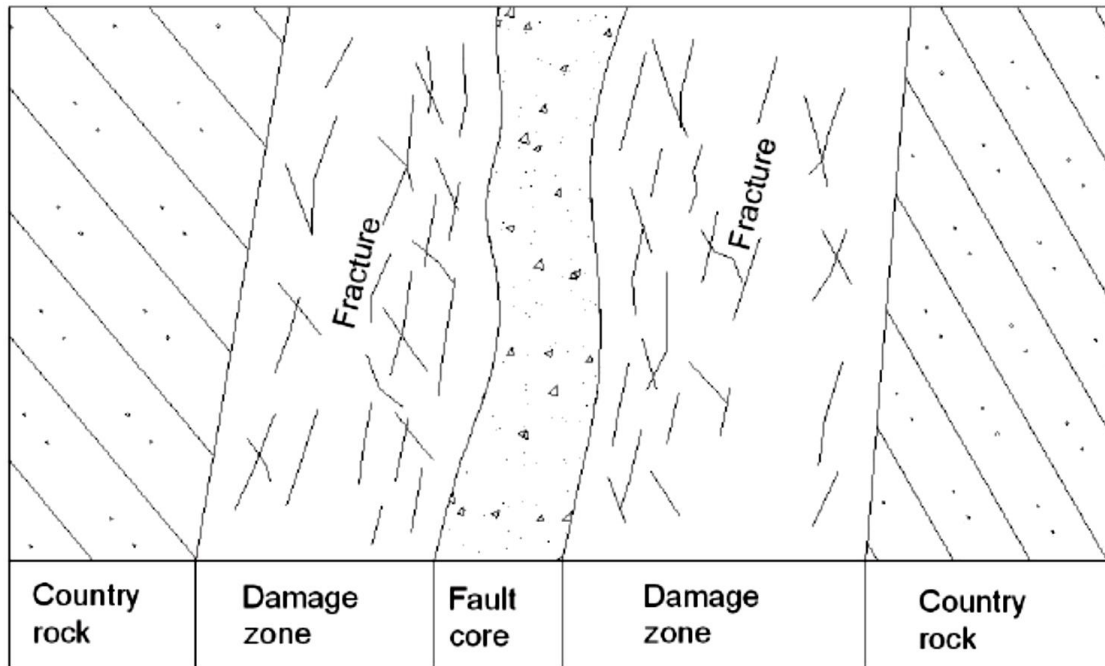


Figure 46: Fault zone architecture (Lin, et al., 2015).

The permeability of faults may change over time, which could generate large changes in nearby streamflow, water tables and the yields of springs. Many active fault zones receive and transports large volumes of groundwater, where the groundwater may be under great fluid pressure. Indications of this can be found in the numerous springs along fault zones (Muirwood and King, 1993; Rojstaczer, et al., 1995; Curewitz and Karson, 1997; Leonard, et al., 1998; Melchiorre, et al., 1999) as well as the extensive sets of mineral filled veins that occur in many eroded fault zones (Phillips, 1972; Gudmundssen, 1999a).

The mechanism of groundwater transport to and along major fault zones are poorly understood, partly as a result of the complexity that are sometimes found in fault zones. Two major units of contrasting permeability are usually found in typical large fault zones, i.e., the core and the damage zone (Bruhn, et al., 2004; Caine, et al., 1996; Evans, et al., 1997; Gudmundssen, 2000). Fault zones may act as a localized conduit or barrier to groundwater. This will depend on the properties of the fault architecture. Table 11 provides information on the evolution of a fault zone and the implications that it has on the hydrogeological classification of the fault. Fault aquifers can be classified into 1) localized conduit, 2) distributed conduit, 3) localized barrier or 4) composited conduit / barrier to groundwater flow and storage (Lin, et al., 2015).

Fault zone material are more susceptible to weathering processes (See Figure 47). The hydrogeological properties may thus change at depth. Key aspects that need to be considered with fault-controlled aquifers is:

- a) The investigation of the development of the fault – structural geology;
- b) The conceptualization of the fault aquifer – hydrogeology; and
- c) The identification of fault zone heterogeneity and associated hydraulic properties.

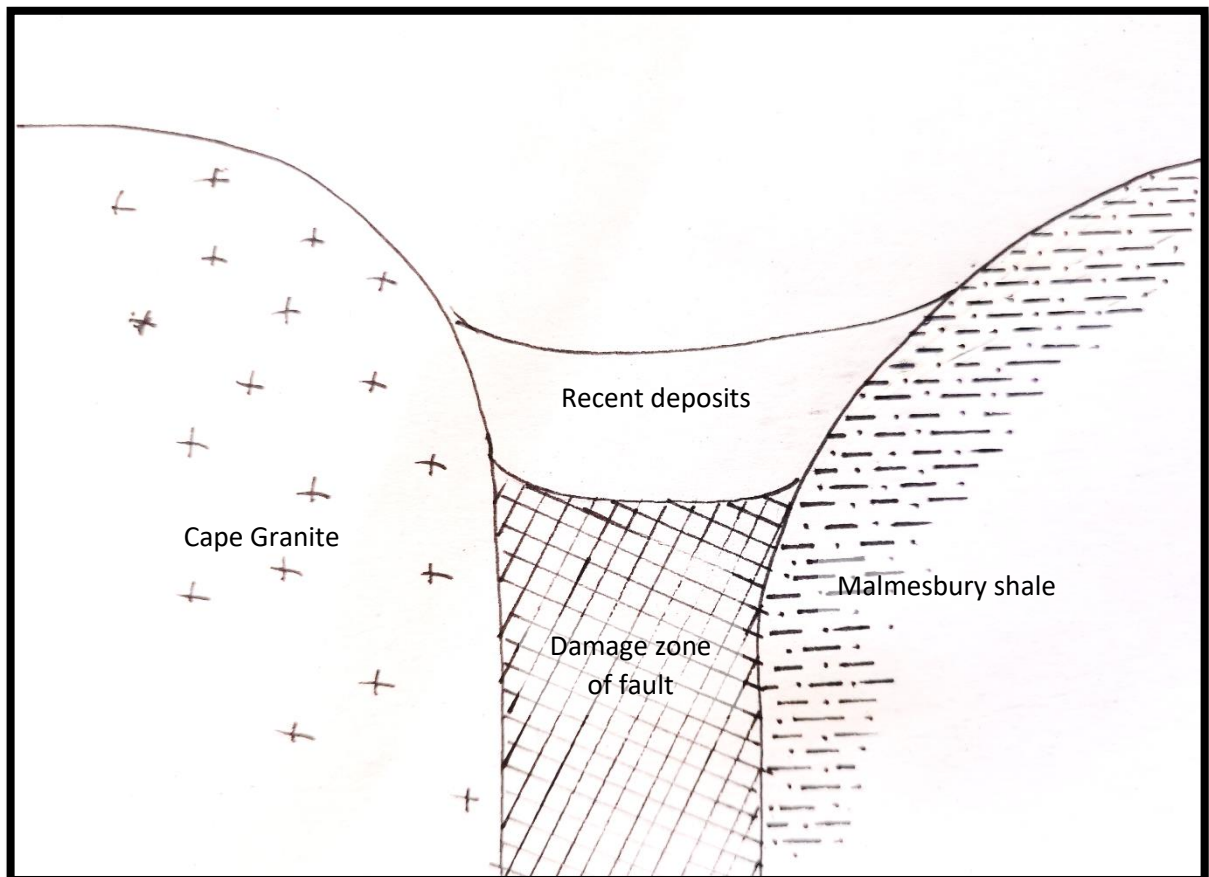
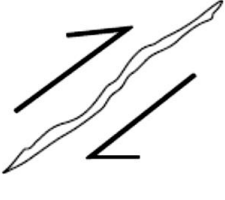





Figure 47: Weathering of the country rock and the damage zone of a fault (Cherry, 2016).

This information all contributes to the establishment of the fault aquifer conceptual model, which leads to the quantification of the groundwater (Lin, et al., 2015). Numerous subzones of breccia and cataclasis increase the overall permeability of the fault zone, which is normally low during inter-seismic periods. There are certain conditions for a fault zone to influence groundwater flow, changing the fault zone to a sink, instead of a barrier. These criteria include that the fault zone must have a higher permeability than the host rock, and the trend of the fault zone must coincide as much as possible with the natural groundwater flow of the region. An active fault zone also tends to have a higher permeability than an inactive fault zone (Gudmundssen, 2000).

The features in the Cape Granite Suite that can be favourable for groundwater occurrence includes 1) zones of weathering, 2) fractures and faults, 3) dyke contacts, 4) metamorphosed contact aureoles in the Malmesbury Group host rock, 5) contact zones with granite bodies, and 6) areas overlain by saturated Cenozoic unconsolidated sediments. The Colenso Fault System thus provides a potential water-bearing system that can provide significant volumes of groundwater. Well-developed breccia zones such as the ones along the Darling batholith have the potential to increase the yields from the Colenso Fault System (Woodford, et al., 2003). Woodford, et al (2003) did a desktop assessment of the area based on available information. No actual groundwater exploration has been done in the vicinity of the Colenso Fault System, except for the geophysics that was done and the boreholes that was drilled by DWS in 2006 (Van Kleef, 2006; De Klerk, 2006). Normal faults usually provide more successful sites for the exploration and exploitation of groundwater resources. This can be attributed to the fact that the tensile stress acting on the fault leads to more open fractures along the fault zone. Most active faults can be found in Quaternary materials, as they tend to be mostly uncemented. Most faults in South Africa tend to be lithified and act as aquicludes because of a lack of neotectonics activity (Lin, et al., 2015). The Colenso Fault system has been active in recent years, with seismic activity in the Paternoster area in January 2012 (Havenga, 2012).

Table 11: Evolution of fault zone with implication for hydrogeological classification of fault (Lin, et al., 2015).

1. Localized conduit	2. Distributed conduit	3. Localized barrier	4. Composite conduit/barrier
Fault core increasing →			
			
Ideal borehole site, Large scale channel flow	Ideal borehole site Dual porosity	No flow boundary	Borehole site at fracture zones; Preferential flow; Boundary control flow and recharge

It is important to understand the geological setting of the Colenso Fault System, to gain a better understanding of the structure itself. The Colenso Fault System is one of the largest crustal structures in the Western Cape. It has an intensely veined core

and is a deep reaching structure. It is rooted in the deeper parts of the crust (more than 25km below surface) (Kisters, et al., 2002) and it separates granites of different compositions lying on either side of the fault zone (Kisters, 2018). The Saldania Belt in which the fault zone occurs is composed of a number of Malmesbury basement inliers, that is exposed in mega-anticlinal hinges of the Permo-Triassic Cape Fold Belt (Woodford, et al., 2003).

The three Malmesbury terranes show different tectonic styles and degrees of deformation (Visser, 1998). Later work by Belcher (2003) indicates that there is only minor compositional difference between the Moorreesburg Formation (Swartland Terrane) and the eastern part of the Tygerberg Formation (Tygerberg Terrane) in areas where there are outcrops of the metasediments along the fault zone. The Tygerberg Terrane is generally light, upright, northwest striking folds with newer hinge zones. The kinematic history of the early phase shows ductile dextral shearing in a 320° direction which resulted in mesoscopic drag, resulting in folds and complex minor folding (Von Veh, 1983).

A later orogenic episode caused changes that overprinted a penetrative foliation, followed by brittle northwest striking sinistral shear. It would seem that the Swartland Terrane has a more complex deformational history, that is visible in only a few isolated outcrops. The southern and western areas contain upright folds slightly inclined to the southwest. The second phase consists of north-northeast striking open cross-folds that occurs commonly. The northeast portion of the lower stratigraphic units are exposed in northwesterly-elongated domal structure called the *Swartland Dome*. A third phase of deformation displays different orientation and intensities of deformation. It is mostly evidenced by northwest- or southeast-plunging folds (Woodford, et al., 2003).

The faults in the area are dominantly northwest trending and presents as near vertical normal faults. The fault systems are characterized by the extensive development of quartz and carbonate veining, brecciation and mylonitisation, with occasion hydrothermal iron-manganese coatings that can be observed. It would seem that the older granitoids of the Cape Granite Suite were syntectonically emplaced as a result of the strike-slip deformation that occurred along the Colenso Fault (Kisters, et al., 2002). Field observations indicate that the Colenso Fault is a system of sub-parallel and anastomosing fault strands that may be up to several kilometers wide (Schoch, 1976; Woodford, et al., 2003; De Beer, 2010; Kisters, 2018) even though it is depicted as a line on regional maps.

The Colenso Fault is described as a major dislocation zone (Roberts and Siegfried, 2014), that is an example of collisional to extensional tectonics in the Pan-African Saldania Belt (Kisters, et al., 2002). The Colenso Fault System stretches about 150km

along the northwest-southeast axis from Northwest Bay on the Atlantic Coast to the south of Stellenbosch, where it is covered by the much younger rocks of the Cape Super Group. Outcrop conditions of the fault is better in the granites, which is more resistant to weathering than in the Malmesbury Group consisting of shales and sandstones. The width of the fault zone and the effects of the faulting and the damage zone varies greatly (Kisters, 2018).

The thick sedimentary deposits that cover the Colenso Fault System as well as weathering (Kisters, 2018) make it difficult to accurately map the location of the fault (see Figure 34). Indications are that it was first described in literature by Schoch (1972). It is only visible above ground in a number of places. This includes the area in Franschoek, on the farm Wintervogel, on the farm Colenso just north of Darling and also just south of Paternoster on the farm Trekossen kraal 104 extending into Northwest Bay. The fault zone can be identified best in the Cape Granite Suite where the granite is mylonitised by synorogenic tectonism and sheared by displacement along the Colenso Fault and its associated dislocations (Roberts and Siegfried, 2014). Massive quartz-carbonate veining, representing cores of individual fault splays. These form characteristic ridges in the landscape (Kisters, 2018).

The deformation caused by the fault zone is particularly severe in the granite near the extension of the fault, with northwest trending mylonites visible on the farm Trekossen kraal 104 (Schoch, 1972; Roberts and Siegfried, 2014). The Hoedjiespunt Granite of the Saldanha Batholith is intensely sheared and mylonitised, with shear zones separating coarsely porphyritic granite from quartz porphyry. These rocks are both shattered over a width of up to 180m. Dark vertical veins of mylonite transects the granite. The dominant shear direction is northwest with a subordinate easterly direction that is evident in some areas. This shearing is associated with the displacement caused by the Colenso Fault. Similar examples can be found along the Colenso Fault in the Vredenburg Batholith and are indications of the effects of shearing and displacement (Roberts and Siegfried, 2014). The northwesterly trending band of severe mylonitisation at Darling is situated approximately in line with the Trekossen Kraal band, and it exhibits an equal crushing intensity and development (Schoch, 1962; 1972). It is clear from the field observations that there are several sub-parallel bands of crushing. The main deformation occurred before the younger granites intruded into the system, with feebler crushing leaving their imprint along the same zones as the major deformation. (Schoch, 1972).

Schoch (1972) identifies the Colenso Fault as the northeastern boundary of the Darling batholith. Granite outcrops to the northeast of the fault is scarce. The narrow fault zone can be located through the massive though intermittent development of chalcidonic fault breccia with a pronounced northwesterly trend (See Figure 48). A spectacular occurrence of breccia can be found on the farm

Colenso on the southeastern side of the main road to Hopefield. It is a small white hill that is conspicuous in the locally flat terrain. More outcrops can be found on the strike on the farms Môreilig, Klipfontein, Kraalbosdam and Brakrivier. Mylonite, another indicator of fault structures, are located on the fault trend at the farm Hartebeesvlei. The fault is very straight, which makes it useful for the siting of boreholes. A slight rotation to a new trend occurs in the southeastern parts, with the hinge on the farm Môreilig. Lines of small outcrops of chalcedonic breccia indicate subsidiary faults at several localities. A large exposure of chalcedonic breccia with a similar orientation as the secondary faults described above has been found on the farm Green River, with the possibility that its direction may change to follow a similar strike as that of the Colenso Fault before reaching Dassenberg. Other breccia outcrops were found at different localities, indicating that more fault lines may exist in the area as splays of the main fault, but the paucity of outcrops make the tracing of the lines difficult. Schoch (1972) found a high yielding borehole on the farm Weylands, on one of the fault splays. The mylonites, dolerite dykes and linear grouping of large xenoliths show similar trends to the fault trend and provided more information on the system. All of these indicators show that it is possible that various movements occurred along the same vectors that was active at various times during the geological history of the area. There are also indications that the Colenso Fault may connect with the Jonkershoek Fault, the Franschhoek Fault or one of its subsidiaries (Schoch, 1972).

Unpublished data on the structure of the Malmesbury Formation to the southeast of the Darling batholith along the sand-covered southwestern contact provides indications of another regional fault, with unmistakable shearing on the farm Klawervlei. This creates the impression that the Darling batholith may be part of a huge fault block, with the postulated fault block regarded as a graben. This idea was reinforced by the Klipheuvel beds that should the characteristic features of rapid deposition and are situated in the same structure further to the southeast (Visser, 1967). Indications are that the southern portion of the Saldanha batholith may be part of the same graben structure (Schoch, 1972).

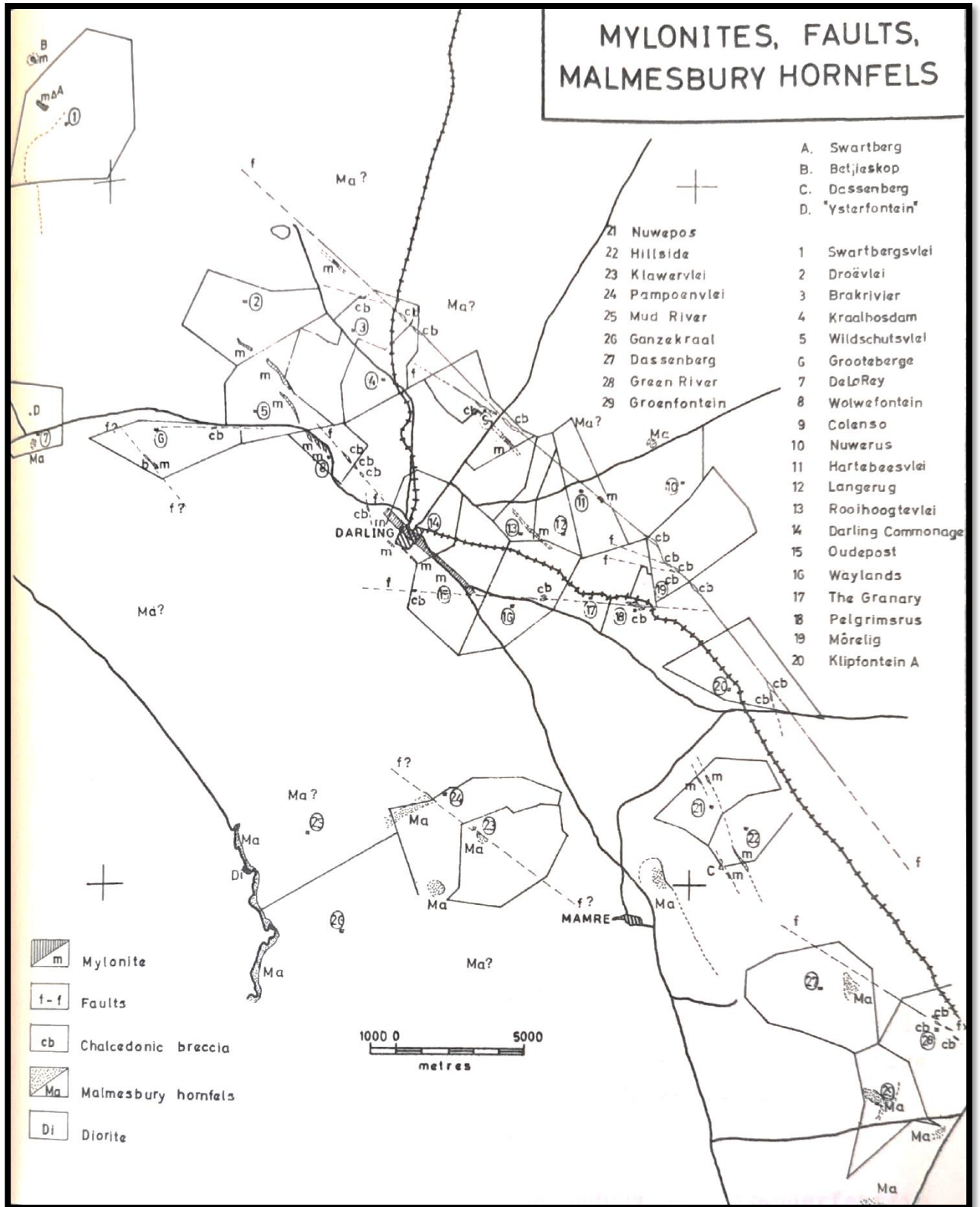


Figure 48: Mylonites, faults and Malmesbury hornfels (Schoch, 1972).

Very few studies had been done on the hydrogeology of the fault system (Peek, 2019). One of the most extensive studies in the sense of the area that it covered, included the geophysics done by De Klerk (2006) for DWAF under van Kleef (2006). The geophysical transect was 1) in the vicinity of Klapmuts, 2) on the farm Wintervogel just south of Malmesbury near the Kalbaskraal site, 3) on the farm Colenso and its vicinity, 4) on the farm Elandsfontein, 5) on the road cutting on the R27 near the Langebaan turn-off and 6) on the R399 between Saldanha and Vredenburg. This led to the drilling of a number of boreholes by DWAF (see Table 12). Some of these boreholes had a very good yield, but it had apparently not been sustainable. They were not subject to further testing or development. The water quality also tends to be brackish to very saline (Vermaak, et al. 2019). The findings of this study created the impression that the groundwater associated with the Colenso Fault System had low yields with brackish to saline water; if the yields was higher, it proved to be unsustainable. This seems to contradict stories of high yielding boreholes with good quality water that was drilled into the fault system.

Table 12: Summary of Drilling Results for DWAF's investigation of the Colenso Fault (after Parsons, 2012; Vermaak, et al. 2019).

Borehole Number	Depth (m)	Blow Yield (L/s)	EC (mS/m)	Main Water Strikes (mbgl)	Geology
BG00062	27	?	715		Granite
BG00063	121	4.9	1178	26,77,102,110	Granite
BG00064	90	Weak	-	27	Granite
BG00065	91	?	1233	-	Granite
BG00066	18	?	952	-	Gravel
BG00067	61	?	575	-	Gravel/shale
BG00068	127	?	830	-	Gravel/shale
BG00069	98	0.0	834	58.64	Clay/shale
BG00070	78	50	869	53	Shale/quartzite
BG00071	121	0.0	4350	33,98,110	Granite
BG00072	181	1.9	424	76.90,105,114,127	Quartzite/shale
BG00073	54	3.5	374	38,52	Quartzite/shale
BG00074	102	?	-	-	Sand/clay
BG00075	66	?	-	-	Shale
BG00076	-	?	771	-	-

Parsons and Associates did work around the Kalbaskraal area in connection to the proposed establishment of a regional landfill site in 2005 (Parsons, 2006; 2012) (see Table 13). The first study done in 2005 seemed to have the same results as that of the DWAF in 2006, namely of low yields and poor quality. Opposition to the project led to further investigations. This included more geophysical work, drilling of deeper boreholes with pumping tests carried out. The picture that emerged from the second study seems to provide a different picture to the hydrogeological characteristics of

the Colenso Fault System – that of a groundwater system that can give good yields with good water quality. Kisters (2018) describes the Kalbaskraal site as overlying a deeply weathered profile of clastic sedimentary rocks belonging to the fault bounded Klipheuwel Group, which includes the lower Magrug Formation and the upper Populierbos Formation. The rocks in the area are tilted, showing moderate to steep dips towards the northeast. The termination and the truncation of the units along the eastern boundary fault testify to the deformation of a sandstone-shale sequence after the deposition of the rocks, which are most probably related to the faulting. Most of the boreholes around the site intersect fresh bedrock at a depth only 60 – 70 m. This was seen in the rock chips in three of the four boreholes from Parsons (2012), which showed a deeply weathered profile at 60 – 70 meters. The rocks show abundant calcite veining, which may correspond to the damage zone around the fault zone (SRK, 2018). The calcite veins may be an indication of groundwater flow or ancient groundwater presence in the fault zone. Available structural data indicates the presence of fault splays (Kisters, 2018), which corroborates the information from De Beer (2010).

Kisters (2018) found evidence of a tectonic fault underlying the Kalbaskraal site. The evidence is mainly circumstantial, as a result of the extensive cover by younger sediments. Lines of evidence include:

- The stratigraphic (age) relationship of the rocks, where the older Magrug Formation is overlying the younger Populierbos Formation in the central and eastern parts of the Kalbaskraal site;
- The extensive veined nature of the rocks in the area corresponds to the presence of a damage zone that surrounds a fault core;
- A deep weathered profile, which indicates the presence of a damage zone;
- The generally steep orientation of the Klipheuwel Group rocks at the site, which could have been the result of local and probably fault controlled activity;
- The presence of silicified ridges to the northwest and along the strike indicates the presence of the fault, with evidence of fault splays to the immediate south of the site.

According to SRK (2018; CGS, 2007) there are a number of fault splays that branch off from the main Colenso Fault line. This includes the Kalbaskraal Fault. To the northwest of the Kalbaskraal site are two more splays branching off from the main Colenso Fault line - the easternmost splay, called the Darling Fault, with the westernmost line called the Mamre Fault (See Figure 49).

Table 13: Summary details of exploratory boreholes in the Kalbaskraal area, with one deep privately-owned borehole and yield testing (Parsons, 2005, 2012; Rosewarne, 2018; Vermaak, et al. 2019)

Borehole Number	Depth [m]	Water strikes [mbgl]*	Final blow yield [l/s]	Rest water level [mbgl]	Constant discharge test yield [l/s]	Sustainable yield [l/s]##	Maximum water level reached after 72 hr [mbgl]	EC at end of CDT [mS/m]
RWS-7 ¹	29.66	c.13	0.3	4.22	-	-	-	95
RWS-8 ¹	n/a	-	n/a	9.15	-	-	-	-
RWS-8a ¹	28.55	c.13	3.0	9.32	-	-	-	401
RWS-9 ¹	28.14	c.18	1.0	0.00	1.01	-	-	185
RWS-10 ¹	27.33	c.21	3.0	0.02	2.97	-	-	82
RWS-11 ¹	21.42	c.12	0.4	3.93	-	-	-	45
RWS-13 ²	100	47, 81 **	2.5	8.84	5.4	5.3	c. 19	90
RWS-14 ²	97	40, 50, 62	5.6	9.52	12	9.1	c. 20	102
RWS-15 ²	90	40, 68	10	0.00	12	7.6	c. 15	50
RWS-16 ²	100	40	0.8	13.4	1	0.25	c. 40	126
RWS-17 ²	108	32, 56	11.9	4.53	10.1	3.8	24.2	81
RWS-18 ²	85	32, 45, 59	13.9	11.11	12.3	6.4	25.4	60
RWS-19 ²	100	37, 45, 55, 84	4.2	12.54	8.40#	3.8	27.5#	83#
RWS-20 ²	100	53, 58, 67	6.7	10.30	12.40#	6.3	24.0#	137#
WV5 ²	146	-	-	8.00	7.1	5.2	25.16	144

¹ Parsons, 2005

²Parsons, 2012

* approximate, from borehole logs

at end of step drawdown test (SDT, 6 h)

** figure in bold denotes main water strike in terms of blow-yield

assumes no interference from other boreholes

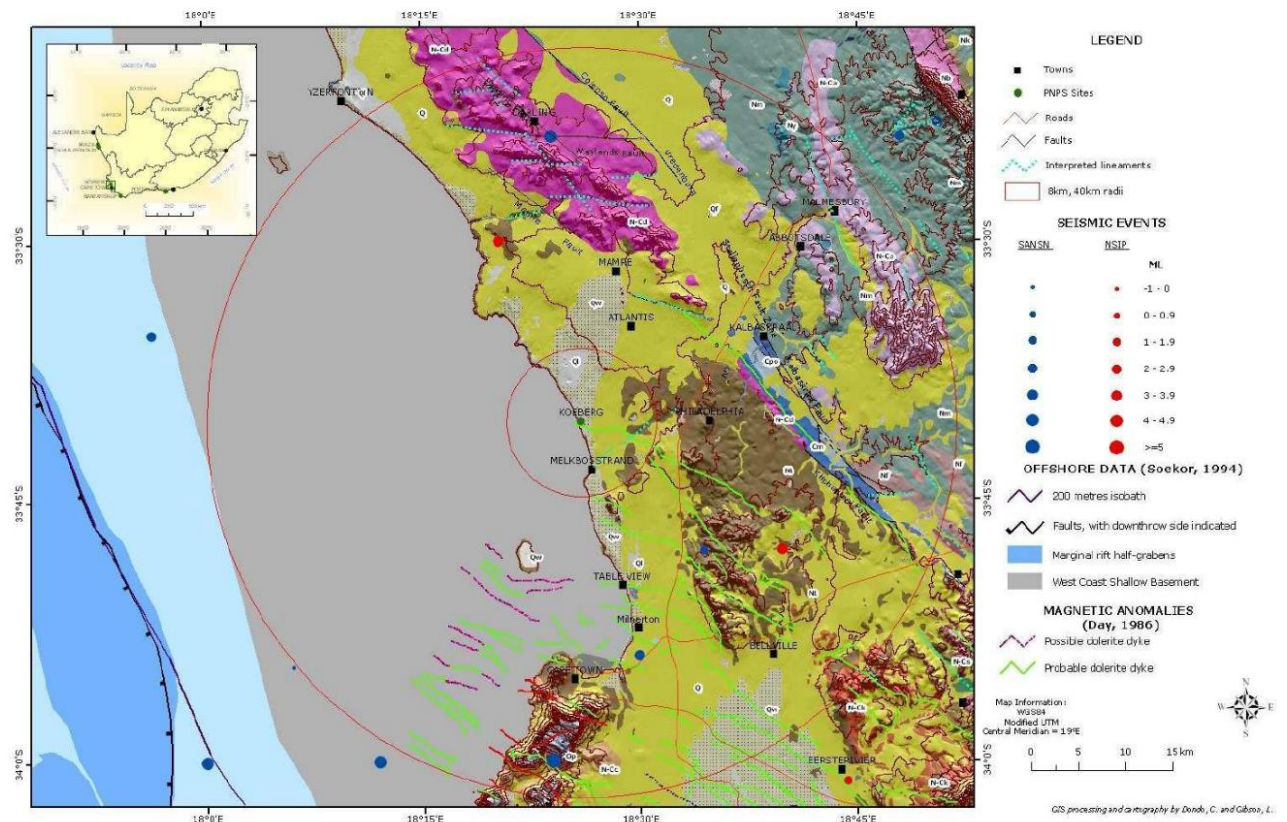


Figure 49: Geological map of the Dufnefontein Nuclear Site Area with the 8km and 4km radii that guide the geological investigation (CGS, 2007; SRK, 2018).

SRK (1996; 1998) did some groundwater exploration in the towns of Riverlands, Chatsworth, Kalbaskraal and a number of other communities in the area. The results of these studies are given in Table 14. Three of the Riverlands boreholes later formed the basis for the Riverlands Government Water Scheme, opened by the Department of Water Affairs in 1998. The Riverlands scheme is still in operation according to the Swartland Municipality. Key conclusions that came out of the investigations for these areas is that it is possible to drill successful boreholes if they are drilled directly into the fault zone, that they need to be at least 75 meters deep, long-term yields are much lower than drilling blow yields and that the water quality is good to medium (SRK 1996; 1998; Vermaak, et al., 2019a).

Table 14: Summary of SRK borehole details in the Chatsworth, Riverlands and Kalbaskraal areas (SRK, 1996; 1998; Vermaak, et al., 2019a).

Borehole	Date	Area	Depth (m)	Geology	Water strikes (m)	Blow-yield (L/s)	Tested yield (L/s)	EC (mS/m)
BH1	1996	Chatsworth	130	Klipheuwel shale	?	0.60	NA	-
BH2	1996	Chatsworth	132	Klipheuwel shale	?	0.06	NA	-
BH3	1996	Riverlands	117	Malmesbury shale	-	0	NA	-
SRK1	1996	Riverlands	75	Malmesbury shale/phyllite/CF	48, 60	10.00	1.5	38
SRK2	1996	Riverlands	105	Malmesbury shale/phyllite/CF	81, 84	10.00	3.5	64
SRK3	1998	Riverlands	140	Malmesbury shale/phyllite/CF	76, 82, 118	7.60	2.0	40
SRK4	1998	Riverlands	140	Malmesbury shale/phyllite/CF	77,115	7.00	-	-
SRK1	1997	Kalbaskraal	45	Malmesbury shale/phyllite/CF	?	?	2.0	144
SRK2	1997	Kalbaskraal	105	Malmesbury shale/phyllite/CF	84,102	20.00	?	?

Stellenbosch municipality needed to find an additional water source for the towns in its municipal area during the recent drought (2015 – 2018) in the Western Cape. GEOSS (2018) targeted the Colenso Fault in the Klapmuts area to augment the municipal supply from the Western Cape Water Supply System. The results of the drilling are given in Table 15. The table also contains the information from two boreholes that was part of a hydrogeological investigation SRK did for Distell (Visser, 2018).

Table 15: Summary of exploration boreholes in the Klapmuts area (GEOSS, 2018; Peek, 2019; Visser, 2018).

Borehole Number	Depth [m]	Water strikes [mbgl]*	Final blow yield [l/s]	Rest water level [mbgl]	Constant discharge test yield [l/s] (duration)	Maximum water level reached after 72 hr [mbgl]	EC at end of CDT [mS/m]
KM_EXBH_1	200	45, 51, 55	20	33	4.5 (2880 min)	55	72
KM_EXBH_2	180	43 , 136	3	14	2.5 (1440 min)	43	43.2
KM_EXBH_3	156	68	6.6	15	1 (1440 min)	45	33.2
KM_EXBH_4	250	94, 106	2	15	2 (1080 min)	100	27.0
KM_EXBH_5	250	43, 76	1	25	1.4 (600 min)	65	31.0
KM_EXBH_6	250	85, 127	2	-	-	-	-
KM_EXBH_7	Not drilled	-	-	-	-	-	-
KM_EXBH_8	247	38 , 180	1	-	-	-	34.7
KM_EXBH_9	200	112	0.1	-	-	-	-
KM_EXBH_10	150	33 , 57, 67	1	-	-	-	-
KM_EXBH_11	119	57	4	18	7.3 (1200 min)	50	64.5
KM_EXBH_12	102	52	4	-	-	-	-
KM_EXBH_13	120	78	0.5	-	-	-	-
KM_EXBH_14	Not drilled	-	-	-	-	-	-
KM_EXBH_15	120	54 , 75	7.4	10	4.5 (1440 min)	50	74
KM_EXBH_16	120	-	-	-	-	-	-
KM_EXBH_17	150	120	0.5	-	-	-	-
M_EXBH_18	91	36 , 52, 71	7	-	-	-	-
KM_EXBH_19	100	30, 42, 59 , 80	5	-	-	-	73.0
KM_EXBH_20	130	85 , 105	2.2	-	-	-	30.0
KM_PBH_1	80	45	15	30	15 (960 min)	55	61.0
KM_PBH_2	80	44	15	39	10 (1440 min)	55	119.0
Old_Klapmuts_BH	150	26 , 53 , 114,146	20	11	6 (1440 min)	55	71.7
DS ₁	203	-	5.0	21.5	4.1 (60 h)	-	31.7
DS ₂	186	-	5.3	17.79	4.5 (72 h)	-	43.1

As most of the South African fault systems show a lack of neotectonics activity and tend to be lithified, they often act as aquicludes (Lin, et al., 2015), and therefore it is easy to generalize this to all fault systems in South Africa. The result may have been very limited groundwater studies on fault systems in the country in general. The Colenso Fault System will thus not be unique in this, and the possibility thus exists of a number of opposing understandings of the fault system in groundwater system.

The number of hydrogeological studies above only provides snapshots of the characteristics of the Colenso Fault System, puzzle pieces to the whole system. It shows that the transmissivity and yield of the fault zone is variable. It depends greatly on the site-specific characteristics, depth of the boreholes and whether boreholes have managed to hit the fault or the damage zone. It is clear that depth plays a role in the groundwater characteristics of the system, as do the lithological composition of the country rock and other formations associated with the system. The studies do not provide a complete picture of the influence that the fault system may have on the groundwater systems of the Berg River catchment area.

The Colenso Fault System may be classified as a minor aquifer as a whole, or in part as for the Kalbaskraal site (Parsons, 2005; 2012) using the aquifer classification system developed by Parsons and Jolly (1994) and Parsons (1995). The reason for this is that it is seen as a low yielding system with poor quality water. Results from other groundwater studies do indicate that there are localized areas along the Colenso Fault System that may have the characteristics of a major aquifer. One of these is the blow yields greater than 5L/s at some of the boreholes above. Not enough is known about the geohydrology of Colenso Fault System yet, as the puzzle pieces and sites have not been linked. It will therefore be necessary to do further investigation to determine what role the Colenso Fault System play in the groundwater systems of the Berg River catchment area. Woodford, et al. (2003) has done a desktop assessment of the potential yield from parts of the Colenso Fault System (See Figure 54 and Table 18).

The palaeochannels and the fault systems in general are important drivers of the groundwater flow (Lin, et al., 2015), and it could be very important to the hydrogeology of the Lower Berg River Aquifer System. It will be discussed further in Chapter 5.

3.8 Water Resources

3.8.1 Surface water

The Berg River is the only permanent water course found in the region and is tidal over part of its length (Noble, 1976). The tidal action may be noticeable up to 25km inland (Timmerman, 1985a). The peak runoff in the river is the result of winter rainfall between May and September in the catchment of the Berg River, with most of it falling in the Franschhoek valley. The mean annual runoff before the completion of the Misverstand weir in 1978 was $1\ 033 \times 10^6 \text{m}^3$ (See Figure 50). The weir is about 60km inland. Yearly runoff in the lower part of the Berg River was reduced to $267,7 \times 10^6 \text{m}^3$ after the weir became operational (K.M.G. Timmerman, 1985; Timmerman, 1988).

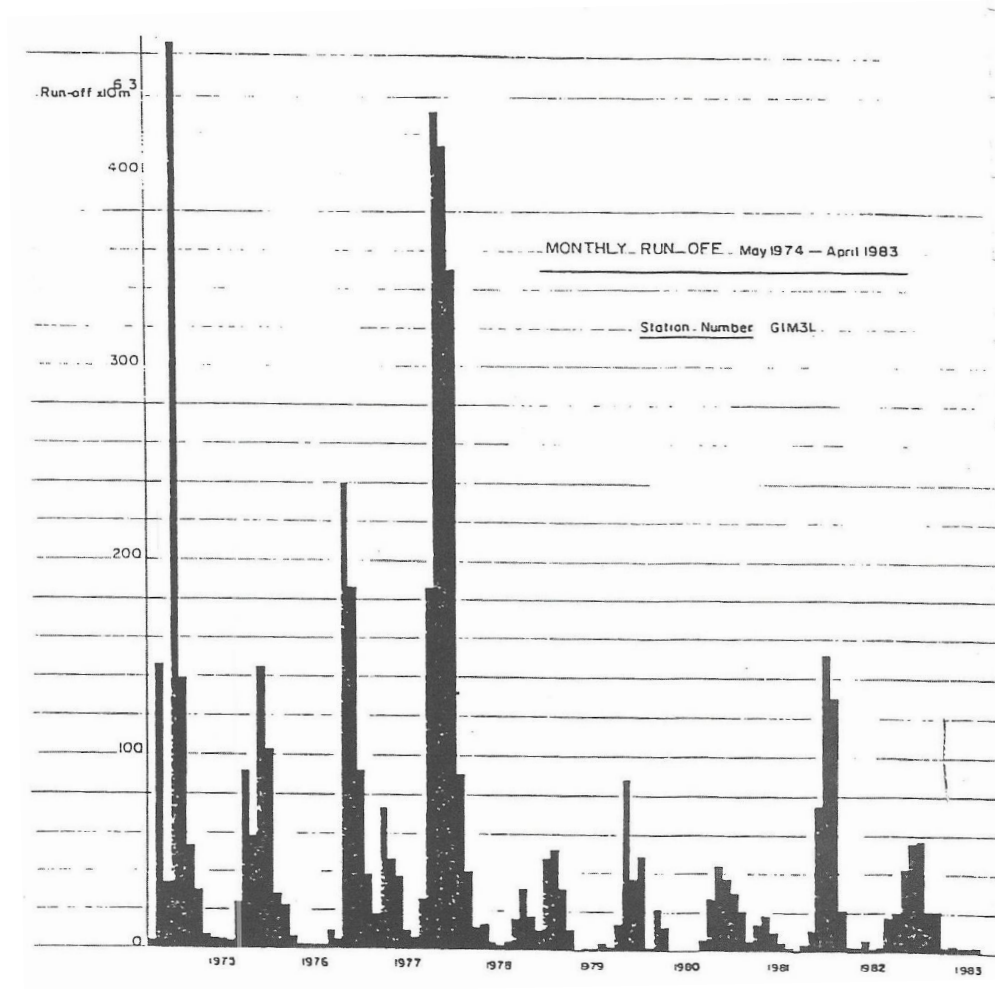


Figure 50: Monthly run-off in the Berg River (after K.M.G. Timmerman, 1985; Timmerman, 1988).

Ephemeral streams drain the rest of the region (Noble, 1976). These include the Kuilders River north of the Berg River and the Brak, Groen and Sout Rivers south of the Berg River. The Kuilders River is a tributary of the Berg River that runs from the TMG escarpment above Aurora, draining part of the Adamboerskraal aquifer unit area. The last three rivers drain the area north of Darling before flowing into the Berg River. The Modder River with the Kransduinen River as tributary, the Dwars River South and the Dwars River North with a number of smaller unnamed rivers flows from the Mamre or Darling hills towards the coast. Most of these rivers derive their flow from beyond the sand covered areas (Timmerman, 1988).

Vleis and pans are found in the flood plain of the Berg River, as well as along the Groen River. Natural springs can be found along the eastern boundary the rivers where the watertable intersects the slopes of the Kuilders, Brak, Groen and Sout Rivers, as well as along the divide between the Sandveld and the Langebaan Road

Plain (Timmerman, 1988). Dune slack wetlands can also be found in the area, especially on the Elandsfontein and Grootwater Aquifer Units.

3.8.2 Groundwater

A request by the Cape Provincial Administration to the Geological Survey led to the investigation of potential groundwater resources for the establishment of a residential and industrial development in the vicinity of Mamre (Vegter and Kok, 1977). This development is today known as Atlantis. It was followed by a request from the Department of Water Affairs in 1974 for groundwater exploration at Geelbek, at the southern end of the Langebaan Lagoon to provide water for the Saldanha harbor. Strong boreholes were located along the Misverstand – Saldanha pipeline, and thus the investigation focused on the Langebaan Road area rather than the Geelbek area. Gravimetric and seismic surveys were done during these early investigations, followed by the drilling of a number of boreholes. By early 1977 a total of 40 boreholes were drilled with 6 of them equipped with Johnson screens and developed as production boreholes (Vegter and Kok, 1977). Additional work by Timmerman (1985a; 1985b; 1985c) and K.M.G. Timmerman (1985) lead to the identification of four aquifer units in the Lower Berg River Aquifer System.

The first and to date the most important of the aquifer units, was the Langebaan Road aquifer unit. The Langebaan Road Primary Aquifer Unit is bounded by the Berg River and the Sout River to the east and north-east, the Vredenburg headland in the north-west, Saldanha Bay in the west and an internal zero-flow boundary stretching roughly from Langebaan to Hopefield in the south (Timmerman, 1985a).

The Langebaan Road aquifer is a heterogeneous anisotropic primary aquifer system (Timmerman, et al., 1985) that can be divided into the upper, unconfined aquifer overlying the semi-confined to confined lower aquifer layer. A clay layer serves as aquitard between the two aquifers layers (Timmerman, 1985b). The base of the system is considered to be impervious and is formed by granite and Malmesbury metasediments. The inferred Colenso fault is the dividing line between the two basement domains which is presumed to be sealed (Timmerman, et al., 1985).

The confined to semi-confined aquifer has a matrix of unconsolidated coarse fluvial Elandsfontyn sediments. These sediments are deposited in an east-west trending palaeo-channel of the Berg River. The sediments consist of poorly sorted angular gravels and sands which are interbedded with peat and clay lenses. The aquifer attains a thickness of up to 60m north-east of Langebaan Road and pinches out towards Saldanha Bay, where finer Aeolian and marine sediments have replaced the Elandsfontyn deposits. Very little is known about the aquifer's extension towards the Berg River. This semi-confined to confined Elandsfontyn aquifer lies largely below sea level (Timmerman, et al., 1985).

The upper aquifer has a twofold hydraulic nature, since it is characterised by primary porosity and permeability in the unconsolidated Aeolian and marine sediments of

the Bredasdorp and Varswater formations, and by secondary flow properties in the semi-consolidated deposits of the Bredasdorp formation (Timmerman, et al., 1985).

The aquitard is formed by discontinuous beds of clay and peat with sandy intercalations of Elandsfontyn age which gives it its leaky character (Timmerman, et al., 1985).

The layers of the Elandsfontein aquifer unit are similar to the Langebaan Road aquifer unit but the sediments have greater thickness. The Elandsfontein aquifer unit lies between the Groen and Brak Rivers to the east, the Darling hills to the south, the sea south of the Langebaan Lagoon and the Lagoon itself on the west and the no-flow boundary to the north (Timmerman, 1985b; Timmerman, 1988).

The Adamboerskraal aquifer unit also has similar layers to that of the Langebaan Road aquifer unit, and it seems to be connected to the Langebaan Road aquifer with the palaeochannel underneath the Berg River (K.M.G. Timmerman; Cole, 2012; Roberts and Siegfried, 2014). The aquifer unit is north of the Kuilders River, with the TMG escarpment and the Wellington-Piketberg Fault to the east, the Papkuils Rivere and the sea to the north and the Berg River to the west. (K.M.G. Timmerman, 1985; Timmerman, 1988).

The Grootwater aquifer unit is along the coast, between the Darling-Yzerfontein Road to the north, the Darling hills to the east, the Modder River to the south. The geology of this aquifer seems to be a combination of that of the three other aquifer units and that of the Atlantis aquifers.

3.8.2.1 Recharge

The main recharge area seems to be the higher dune sands of the Hopefield area (Noble, 1976; Tredoux and Engelbrecht, 2009), as well as the higher lying areas around Elandsfontein Farm (Timmerman, 1988). The groundwater then flows from these high grounds, westwards and northwards towards Langebaan Road. A part of the water continues in a westerly direction towards Saldanha Bay and the rest flows in a northerly direction towards the Berg River (Timmerman, 1985a). Recharge to the semi-confined aquifer is thought to be mainly by downward leakage from the superficial deposits in the dune highlands on the south-eastern boundary of the unit (Timmerman, 1985a; Timmerman, et al., 1985).

No rivers occur in the investigation area and the rivers bordering the area gains water from the system under the piezometric and watertable conditions. Recharge to the aquifer system takes place from direct infiltration of precipitation. (Timmerman, 1985a; Timmerman, et al., 1985). Recharge is possible from the Berg River to the aquifer system under high flood conditions (Seyler, et al., 2016). Recharge to the aquifer has not yet been quantified when the original work was done (Timmerman, 1985a).

One option regarding recharge that has not been considered is that of recharge through faults and fissures in the basement from some of the high TMG mountains in the catchment. The recharge to the Sandveld aquifers (the area north of Dwarskersbos) is considered to come from the mountains, with recharge taking place from the basement upwards (Nel, 2004). This could possibly provide additional recharge to the Lower Berg River Aquifer System. Timmerman (1988), however, discarded this as a possible source of recharge because of the thick clay layer from the weathered basement that would act as an impermeable layer. It was also used in later work (DWAF, 2008).

Sustainable groundwater abstraction depends to a great extent upon adequate recharge, with estimated recharge for most aquifer systems in South Africa ranging between 5% and 10% of annual precipitation. Effective recharge is the amount of rainwater that infiltrates into the vadose zone and actually reaches the main underlying aquifer system. Woodford, et al. (2003) determined the mean annual effective recharge (R_e) from rainfall for their study area using a GRID-based GIS modelling technique, described below:

1. A 50x50m grid of variable recharge rate or factor (R_f) was derived from the mean annual precipitation (MAP) dataset (see Figure 26, after Schultze, 1997), as follows:

$$R_f = [\text{MAP (mm)} / 10\ 000]$$

2. A 50x50m runoff factor (S_f) grid was derived from a percentage slope grid (calculated from 50x50m digital terrain model), as follows:

$$S_f = [100 - \text{Slope}\%] / 100$$

3. A 50x50m lithology factor (L_f) was derived to take into account the variable recharge rates with the various lithological units as follows:

Lithological Unit	Recharge Factor (L_f)
Cenozoic Deposits – Fine- & Medium- grained.	0.90
Cenozoic Deposits – Coarse Scree & Terrace material.	1.05
Cenozoic Deposits – Limestone.	1.10
Table Mountain Gp – Nardouw SbGp.	0.95
Cape Granite.	0.85
Malmesbury Gp – Moorreesburg, Porterville & Berg River Fm.	0.65

4. A 50x50m mean annual effective recharge or R_e (mm) grid was derived for the study area as follows:

$$R_e \text{ (mm)} = \text{MAP} \times R_f \times S_f \times L_f$$

5. The Lower and Upper Limits of R_e were estimated from Shultze's (1997) Coefficient of Variation (%) of Annual Precipitation, which they refer to as an 'index of climatic risk'.
6. The mean annual effective recharge from rainfall for the study area is estimated at $141 \times 10^6 \text{ m}^3$, which equates to an average recharge rate of 3.9% of the mean annual precipitation. The variability of the mean annual groundwater recharge within the study area is indicated in Figure 51.

The mean annual groundwater recharge for the areas relevant to this study is presented in Table 16. The variable lithology, rainfall and topography in the area contributes to the variability of the recharge rate given as percentage of MAP. The recharge percentage for the relevant management areas varies between 1.8% and 5%.

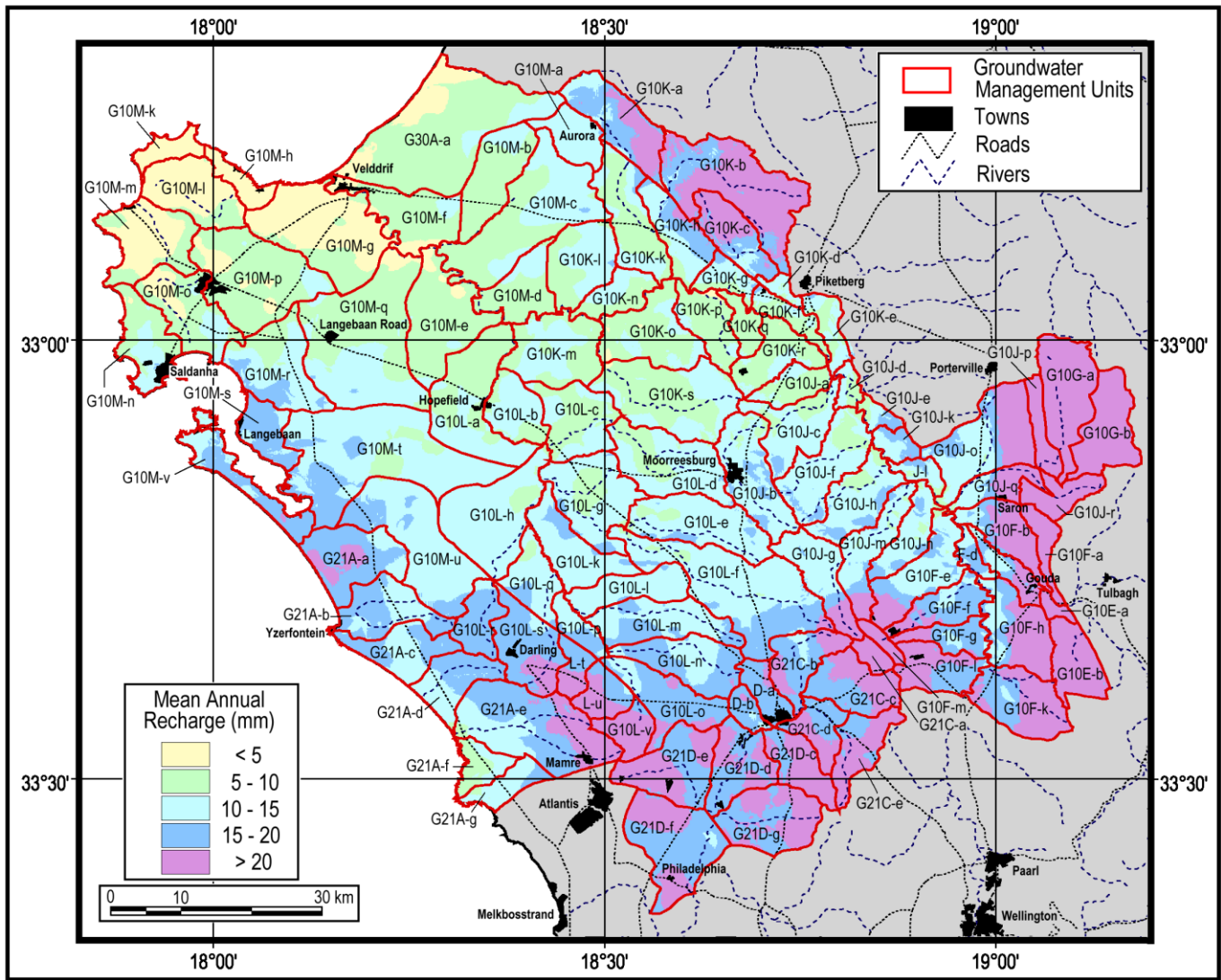


Figure 51: Groundwater Management Units and Mean Annual Recharge for the Study Area (Woodford, et al., 2003).

Table 16: Groundwater Recharge per Groundwater Management Unit (after Woodford, et al., 2003; only relevant management units included).

Unit No.	MAP (mm/yr)	Mean Recharge (m ³ /yr)	Recharge Rate % of MAP	Upper Recharge (m ³ /yr)	Lower Recharge (m ³ /yr)
G10K-a	470	1,778,999	4.3	2,333,802	1,224,196
G10K-b	547	4,451,842	5.0	5,760,762	3,142,904
G10K-c	494	1,359,266	4.5	1,777,260	941,272
G10K-d	382	150,140	3.3	200,187	100,093
G10K-e	370	378,614	3.2	505,986	251,242
G10K-f	348	313,401	2.9	420,025	206,776
G10K-g	362	370,055	3.4	494,548	245,563
G10K-h	402	990,813	3.8	1,314,157	667,470
G10K-k	338	1,006,469	3.2	1,349,774	663,174
G10K-l	349	945,204	3.3	1,267,972	622,429
G10K-m	337	1,084,167	3.2	1,456,634	711,700
G10K-n	327	435,815	3.1	585,999	285,636
G10K-o	333	908,171	2.8	1,219,297	597,036
G10K-p	332	514,877	2.7	691,300	338,453
G10K-q	313	206,403	2.6	278,075	134,734
G10K-r	339	573,092	2.8	768,342	377,835
G10K-s	355	1,509,943	2.9	2,020,330	999,556
G10L-a	333	1,390,650	3.2	1,869,673	911,627
G10L-b	358	672,927	3.3	901,274	444,586
G10L-c	354	899,353	3.1	1,204,589	594,126
G10L-d	381	1,315,675	3.2	1,752,964	878,387
G10L-e	401	1,432,604	3.4	1,902,190	963,018
G10L-f	415	2,913,627	3.6	3,858,055	1,969,199
G10L-g	383	1,362,651	3.3	1,815,285	910,017
G10L-h	361	1,605,900	3.4	2,150,672	1,061,141
G10L-k	395	1,146,474	3.7	1,525,311	767,630
G10L-l	397	830,164	3.6	1,103,920	556,408
G10L-m	418	1,345,266	3.7	1,783,090	907,434
G10L-n	439	1,387,452	3.8	1,830,835	944,060
G10L-o	448	1,492,480	4.2	1,966,015	1,018,953
G10L-p	402	412,542	3.8	547,434	277,652
G10L-q	379	728,597	3.6	971,733	485,455
G10L-r	444	799,987	4.0	1,056,485	543,484
G10L-s	454	1,560,282	4.2	2,055,115	1,065,441
G10L-t	472	540,350	4.4	709,799	370,901
G10L-u	482	807,285	4.5	1,058,035	556,534
G10L-v	528	912,429	4.8	1,186,289	638,572
G10M-a	378	615,972	3.6	822,680	409,264
G10M-b	316	799,930	3.0	1,078,795	521,064
G10M-c	335	1,957,931	3.2	2,629,348	1,286,531
G10M-d	314	599,358	3.0	806,939	391,777
G10M-e	303	1,061,972	2.9	1,435,393	688,539
G10M-f	287	702,143	2.8	950,593	453,694
G10M-g	231	855,421	2.2	1,168,279	542,564
G10M-h	199	101,341	1.8	139,202	63,480
G10M-k	212	115,607	2.0	158,597	72,616
G10M-l	212	377,749	2.0	517,020	238,486
G10M-m	220	471,585	2.2	644,374	298,795
G10M-n	324	742,010	3.2	999,579	484,450

Table Continued					
Unit No.	MAP (mm/yr)	Mean Recharge (m ³ /yr)	Recharge Rate % of MAP	Upper Recharge (m ³ /yr)	Lower Recharge (m ³ /yr)
G10M-o	288	712,386	2.8	964,418	460,354
G10M-p	285	1,216,226	2.7	1,647,883	784,585
G10M-q	318	2,251,572	3.1	3,033,556	1,469,564
G10M-r	357	1,281,627	3.4	1,715,785	847,470
G10M-s	421	761,032	3.9	1,011,069	510,991
G10M-t	372	3,354,049	3.5	4,483,749	2,224,323
G10M-u	394	2,230,726	3.7	2,968,821	1,492,615
G10M-v	412	993,819	3.9	1,317,507	670,124
G21A-a	429	1,593,682	4.0	2,110,496	1,076,860
G21A-b	414	1,208,140	3.9	1,604,952	811,329
G21A-c	412	1,016,811	3.9	1,350,367	683,248
G21A-d	413	941,317	3.8	1,250,022	632,613
G21A-e	450	3,104,019	4.2	4,084,830	2,123,224
G21A-f	337	362,931	3.2	487,511	238,351
G21A-g	386	490,947	3.7	654,280	327,614
G30A-a	285	1,987,363	2.8	2,689,003	1,285,722
TOTAL	368.4	72,441,632	3.39	96,418,261	48,464,941

Historical data was used for these calculations, with different results possible if it is recalculated with more recent data. The main recharge area of the Western Cape will also be during the winter months, when the majority of rainfall occurs. Using MAP for the calculations may lead to a misrepresentation and a generalization of the actual recharge that occurs in the area. It does, however, provide a reasonable basis from which to begin in determining the potential sustainable use of the aquifer systems.

3.8.2.2 Flow directions

The upper unconfined to semiconfined aquifer layer for the Langebaan Road and Elandsfontein aquifer units is essentially one. Flow directions (Figure 52) for this layer is from the higher lying areas towards the north, towards the Berg River and Saldanha Bay, as well as towards Geelbek and the coast south of Langebaan Lagoon. Some of the flow is also towards the Groen and Sout Rivers (Timmerman, 1988; Woodford and Fortuin, 2003; DWAF, 2008; Seyler, et al., 2016).

Flow in the lower aquifer layer is controlled by the palaeochannels in both the Langebaan Road and Elandsfontein aquifer units (see Figure 53). In the Langebaan Road aquifer unit, the flow is from the Berg River towards Saldanha Bay. The lower semi-confined to confined aquifer layer of Langebaan Road aquifer unit is under considerable piezometric pressure, especially in the Langebaan Road area as a result of the overlying aquitard. The flow of groundwater takes place from Hopefield in the south towards Langebaan Road where it bifurcates into a westerly and a north-easterly direction. The granitic barriers with Kleinberg and De Kop as the major outcrops, causes the piezometric surface to rise above the water table in an area of about 30km² north-east of Langebaan Road and creates free flowing wells

(Timmerman, et al., 1985). The flow in the lower aquifer layer of the Elandsfontein aquifer unit is towards the northwest from the farm Sonquasfontein, till it reaches the farm Elandsfontein, where after it turns to flow in a westerly direction towards Geelbek (Timmerman, 1988; DWAF, 2008; Seyler, et al., 2016).

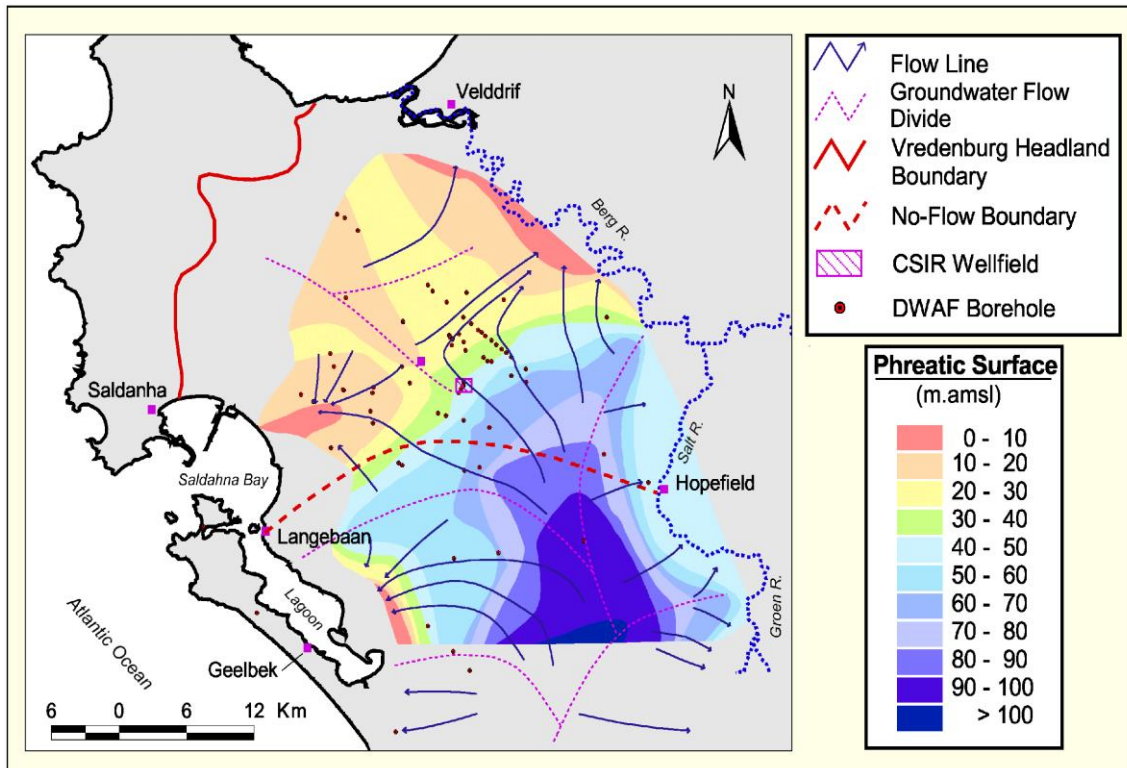


Figure 52: Groundwater contours for the upper unconfined layer with flow directions (Woodford and Fortuin, 2003).

Flow in the Adamboerskraal aquifer unit is toward for both the upper and lower aquifer layers are towards the Kuilders River (south), the Berg River (east), the Papkuils River and the sea in the north (K.M.G. Timmerman, 1985; Timmerman, 1988). In the Grootwater aquifer unit the flow is mostly towards the coast from the Darling hills (Timmerman, 1985a).

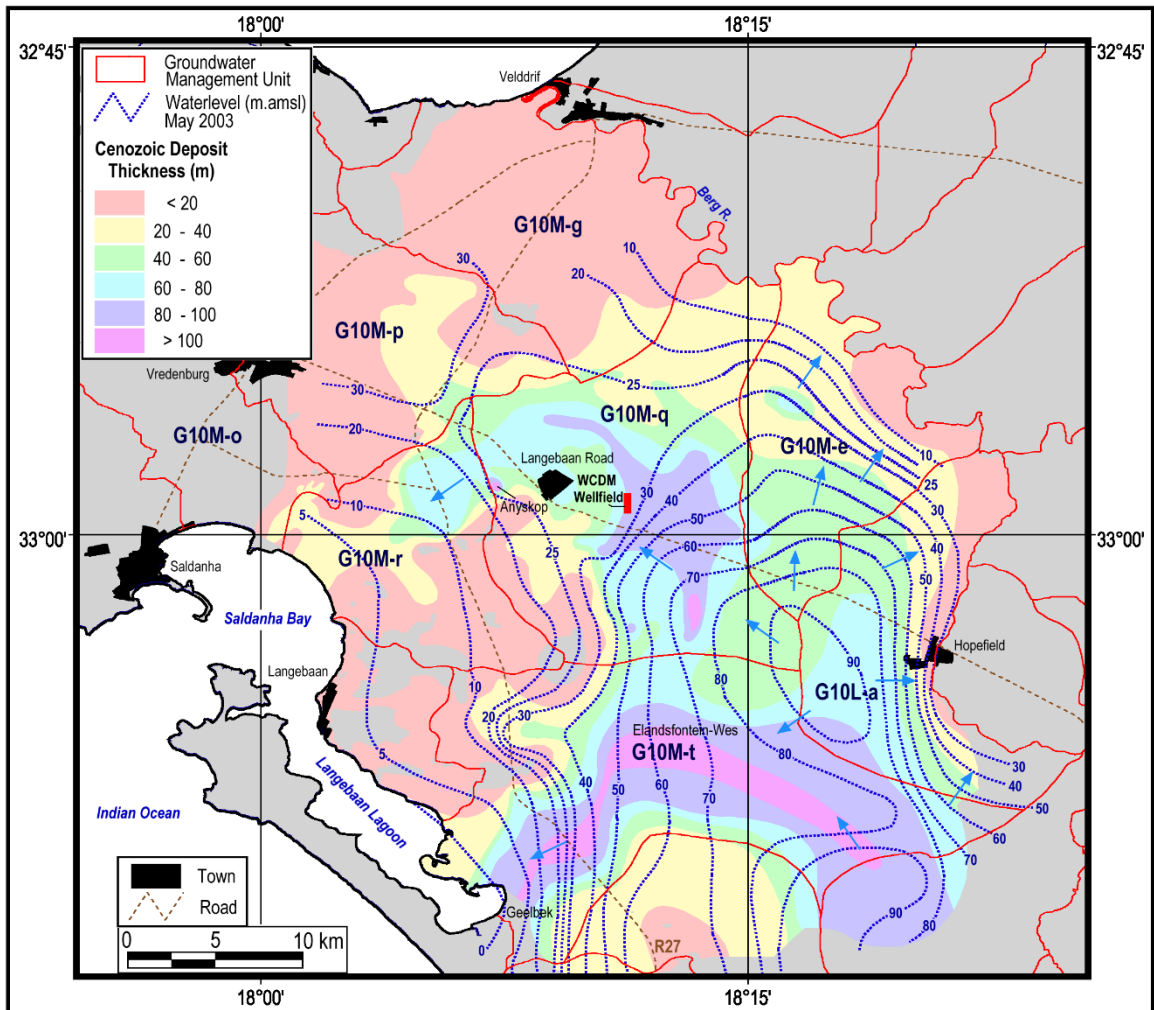


Figure 53: Water level elevation in the Lower Aquifer Unit of the Langebaan Road and Elandsfontein Aquifer Systems and Thickness of Cenozoic Deposits (Woodford, et al., 2003; Woodford and Fortuin, 2003).

3.8.2.3 Yield and storage potential

Vegter and Kok (1977) made an initial assessment of the yield that can be expected from the first investigations in the Langebaan Road area. The estimations of Timmerman (1985; 1988) is higher and included the possibility of mining the aquifers. The findings of the initial exploration work are given in Table 17. The Lower Berg River Aquifer System has a large exploitation potential and a large storage capacity, but it is also linked to sensitive ecosystem. Mining of the semi-confined to confined layers could potentially cause the aquifer layer to become unconfined and then collapse. Seawater intrusion or brackish water intrusion also needs to be managed. It would thus be important to manage the abstraction from the system carefully to ensure that the system is not damaged.

Table 17: Summary of the yield and storage potential for the Lower Berg River Aquifer System.

Reference	Aquifer yield estimate [m ³ /a]	Borehole yields [l/s]	Transmissivity [m ² /day]	Hydraulic conductivity [m/day]	Storage potential [m ³]	Area
Vegter and Kok, 1977	8 – 13 million	5 – 27.5*				Langebaan Road
Timmerman, 1985a	7 – 10 million	40	25 – 1000 [#] 10 – 400	3 – 50 [#]	200 x 10 ⁶	Grootwater
K.M.G. Timmerman, 1985	15 x 10 ⁶ 2 200 x 10 ⁶ (mining)	30	500	25	200 x 10 ⁶ [#]	Adamboerskraal
Timmerman, 1985b	36 x 10 ⁶ 55 x 10 ⁶ (mining)	50	Langebaan Rd: 10 – 4000 Elandsfontein: 50 – 250 QSM 100 – 1000 Springfontyn 50 – 500		Langebaan Rd: 21.9 x 10 ⁶ 200 x 10 ⁶ [#] Elandsfontein: 15.5 x 10 ⁶ 2400 x 10 ⁶ [#]	Langebaan Road and Elandsfontein
Timmerman, 1988	15 x 10 ⁶ (model area) 50 x 10 ⁶					Adamboerskraal, Elandsfontein and Langebaan Road

*artesian flow; [#]unconfined

Woodford, et al. (2003) made an assessment of groundwater development potential for the region managed by the West Coast District Municipality (See Figure 54 and Table 18). The area of the investigation extended further than the study area of this investigation, and only the relevant quantities were given. It is interesting to note that the groundwater development potential of some areas of the Colenso Fault Zone were included in the investigation. Even though it was mostly a desktop investigation, it provides valuable information on the groundwater resources in the area.

Table 18: Summary of Groundwater Development Potential for the selected Target Areas – selection of sites (Woodford, et al., 2003).

Target Zone (ET)	Area of ET [Area of GU] (km ²)	Ave. EC (mS/m)	Mean Annual Recharge [Dry Season] (x 10 ⁶ m ³ /a)	Exploitation Potential [Dry Season] (x 10 ⁶ m ³ /a)	Description of Aquifer
ET-20	69.8 [573.0]	141	11.86 [8.17]	3.61 [2.49]	Franschhoek – Saldanha FZ, contact Malmesbury Gp and Cape Granite.
ET-21, -23, -24 & -25	31.1 [232.2]	290	4.04 [2.74]	1.35 [0.92]	Franschhoek – Saldanha FZ, contact Malmesbury Gp and Cape Granite.
ET-22	38.4 [279.7]	400	4.09 [2.75]	1.40 [0.94]	Composite primary and fractured Malmesbury bedrock aquifer system.
ET-26	5.47 [53.7]	250	0.39 [0.25]	0.12 [0.08]	Franschhoek – Saldanha FZ, contact Malmesbury Gp and Cape Granite.
ET-27	87.2 [307]	189	5.41 [3.68]	3.84 [2.61]	Composite primary – fractured bedrock aquifer – Grootwater AS.
ET-28	86.0 [144.2]	186	2.45 [1.66]	1.60 [1.08]	Composite primary – fractured Granite bedrock aquifer – Elandsfontein [B] AS.
ET-29	323.0 [419.9]	182	7.53 [4.99]	4.80 [3.20]	Composite primary – fractured Malmesbury bedrock aquifer – Elandsfontein [A] AS.
ET-30	321.5 [626.9]	234	5.38 [3.51]	2.75 [1.80]	Composite primary – fractured Malmesbury bedrock aquifer – Langebaan Road [A] AS.
ET-31	39.2 [132.6]	600	1.50 [0.99]	0.89 [0.58]	Composite primary – fractured Granite bedrock aquifer – Langebaan Road [B] AS.
ET-32	254.0 [442.9]	560	4.24 [2.77]	2.43 [1.59]	Composite primary – fractured Malmesbury bedrock aquifer – Adamboerskraal AS.
Total	1255.67 [3212.1]	-	46.89 [31.51]	22.79 [15.29]	

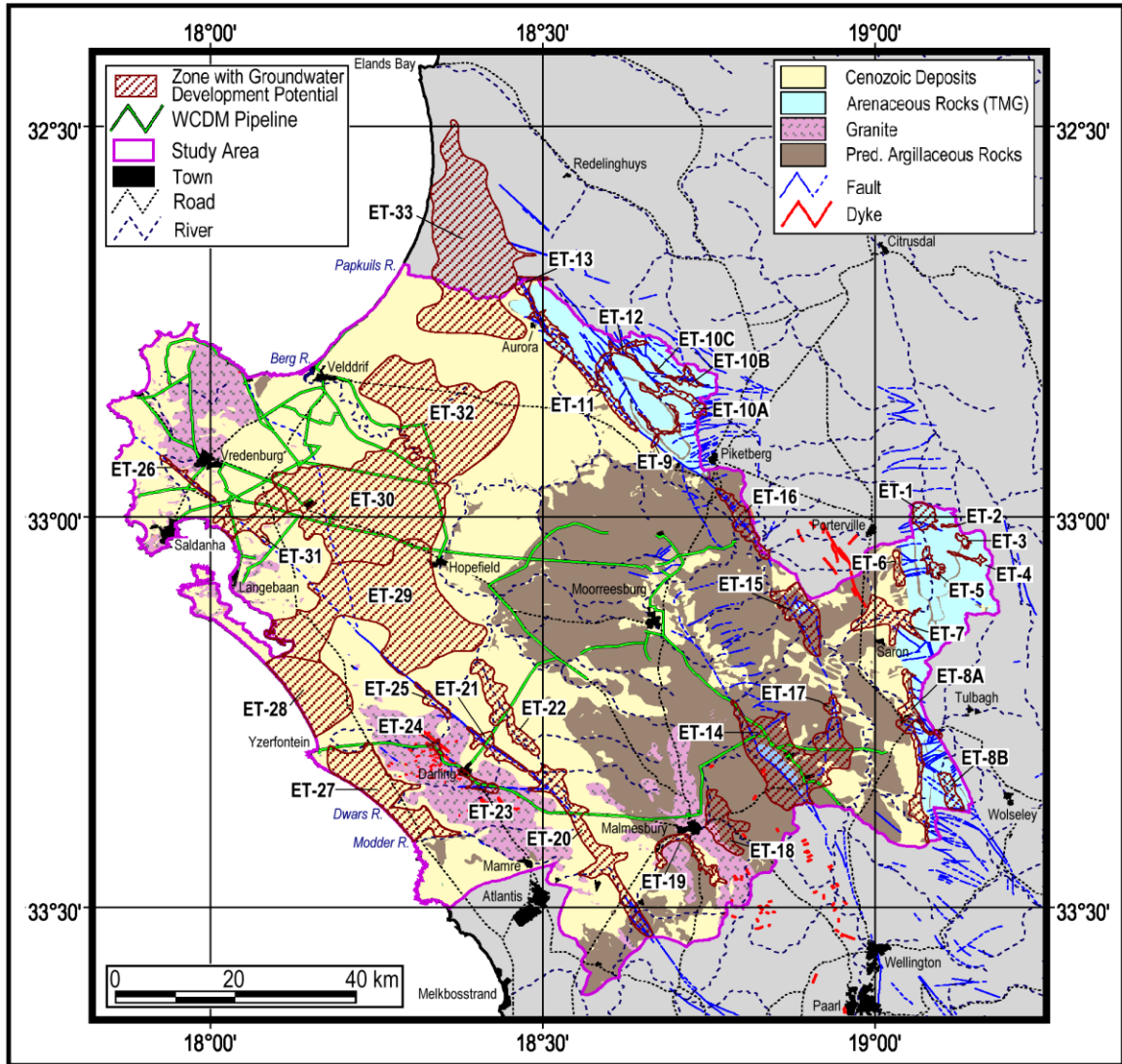


Figure 54: Zones of Groundwater Development Potential in relation to the existing Saldanha-Berg and Swartland water reticulation scheme (Woodford, et al., 2003).

3.8.2.4 Discharge and abstraction

Discharge takes place through gaining rivers, evapotranspiration, spring flow, abstraction and the natural underflow towards Langebaan Lagoon, Saldanha Bay and the Atlantic Ocean (Timmerman, 1985a; Timmerman, et al., 1985). Woodford (2004) provided some estimates of the values of the natural discharge in L/s (Figure 55).

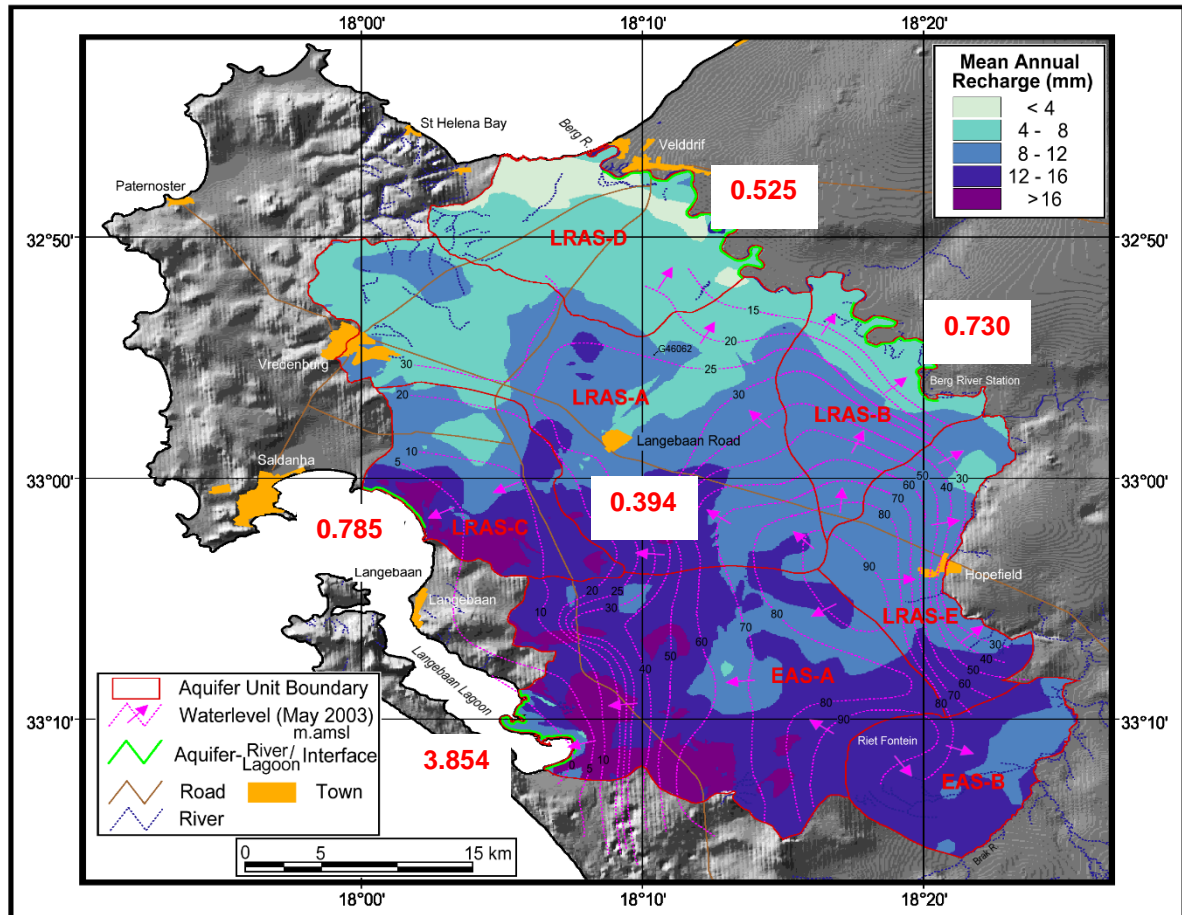


Figure 55: Natural discharge [L/s] from the Langebaan Road and Elandsfontein aquifer units to the rivers, wetlands, pans, springs and the sea (Woodford, 2004).

The West Coast District Municipality is the largest single user of groundwater out of the Lower Berg River Aquifer System. The wellfield became operational in December 1999. Figure 56 shows the cone of depression after the wellfield had been operational for a number of years. The elongation of the cone of depression in an east-west line correlates with the direction of the palaeochannel. The loop towards the south was a bit unexpected, especially considering the no-flow boundary between the Langebaan Road and Elandsfontein aquifer units that was postulated by Timmerman (1985b; 1988). The impact that can be seen along the R45 towards Hopefield may be linked to the palaeochannel mapped by Smith, 1982, and also the fact that some of the recharge is coming from that direction (Timmerman, 1988; DWAF, 2008).

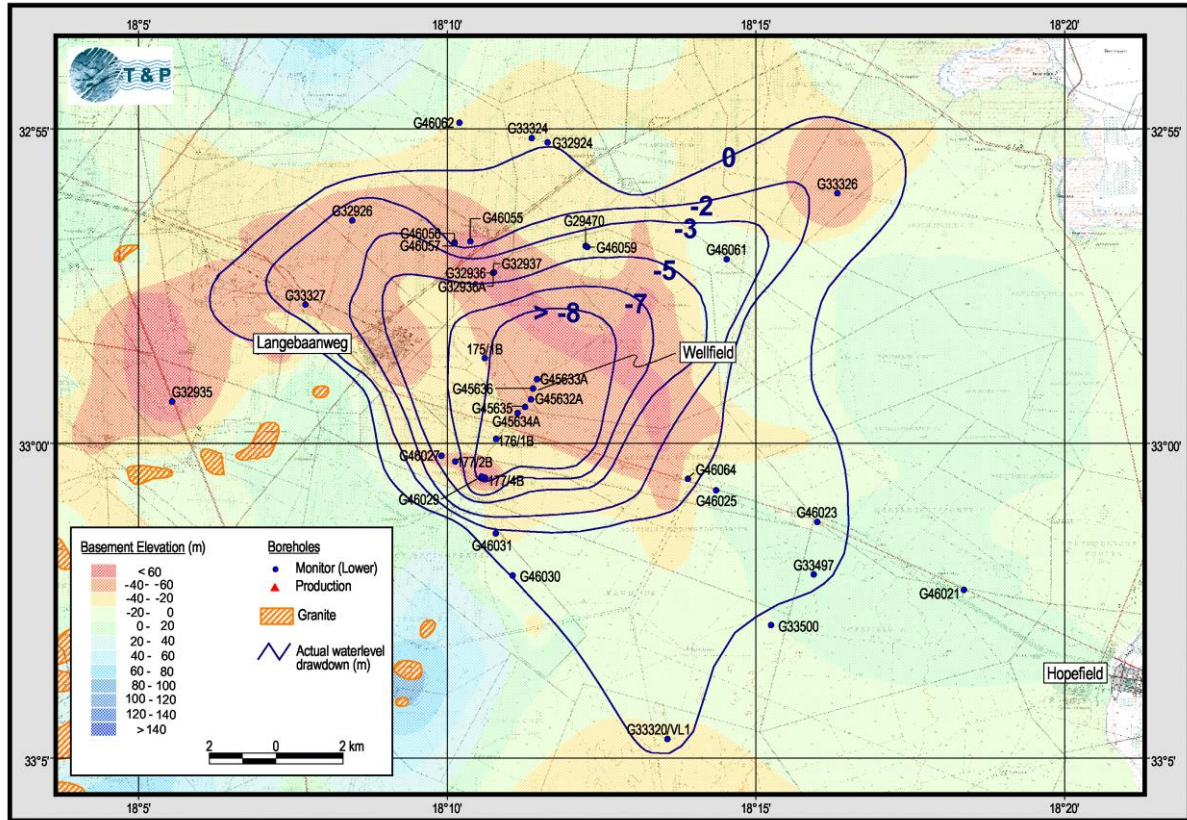


Figure 56: Cone of depression associated with the Langebaan Road wellfield after a number of years in operation (Woodford and Fortuin, 2003).

Figure 57 gives an indication of groundwater use in the Langebaan Road and Elandsfontein aquifer units. The size of the dot gives an indication of the volume abstracted. Most of the points are wind pump, which would abstract a low volume. The large dots towards the southeast are on the farms Theefontein and Uilenkraal, where pivot point irrigation took place (Woodford and Fortuin, 2003). The reason for the small abstraction volumes, especially on the Langebaan Road aquifer unit, was a result of the declaration of the Saldanha Subterranean Government Water Control Area that was declared in September 1976. Groundwater would thus have been used for domestic use and stock watering.

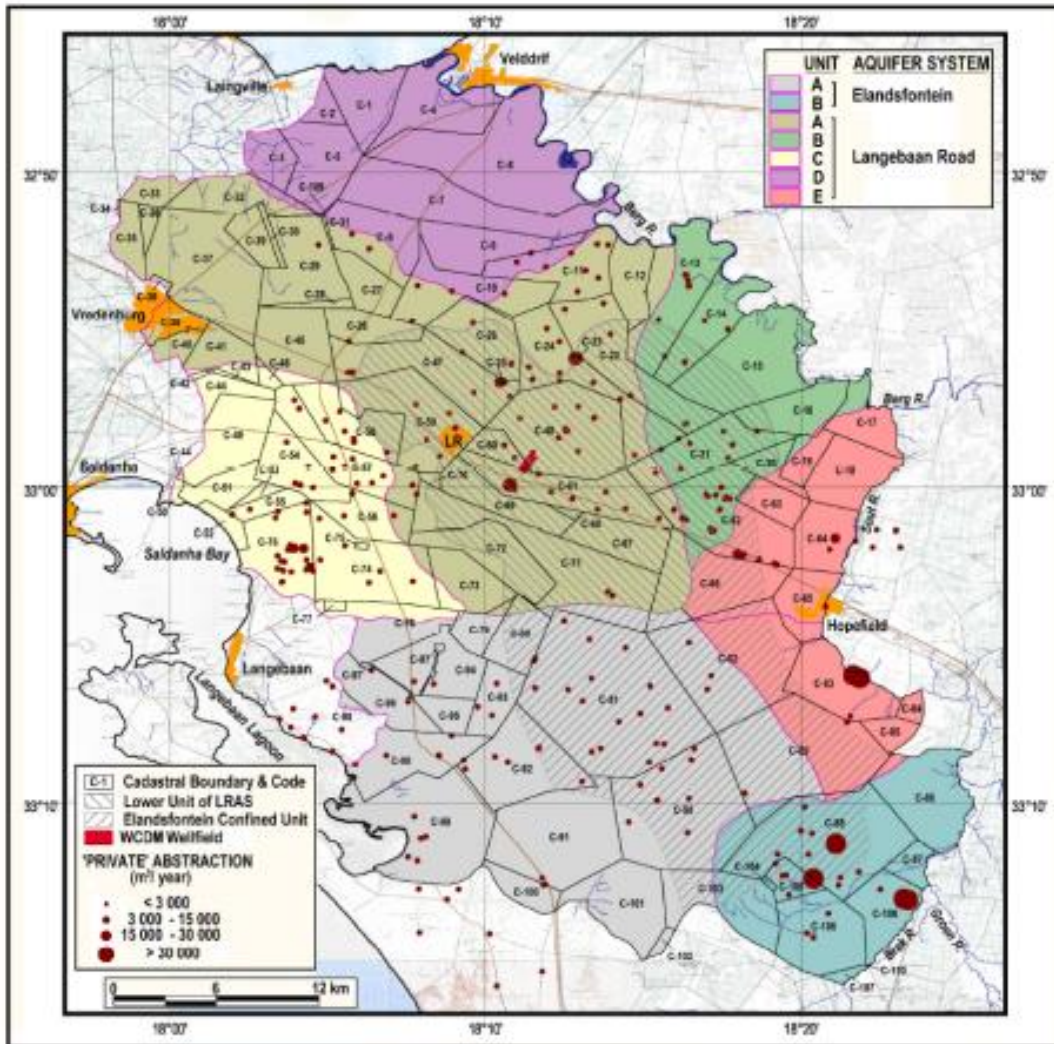


Figure 57: Groundwater use in the Langebaan Road and Elandsfontein aquifer units (Woodford and Fortuin, 2003).

3.8.2.5 Groundwater quality

The water quality of the groundwater in the area is generally good (below 100mS/m), with the upper aquifer layers mostly of a poorer quality than the lower aquifer layers. Figure 58 provides the information for the wider area managed by the WCDM, while Figure 59 provides an indication of the water quality using the electrical conductivity (EC) for the Langebaan Road and Elandsfontein aquifer units. The southern and central part has good quality, that deteriorates towards the north and the west, where brackish water is found close to the Berg River and the sea (Timmerman, 1988; Woodford and Fortuin, 2003). Figure 60 (upper unconfined layer) and Figure 61 (lower semi-confined layer) show the water quality around the wellfield.

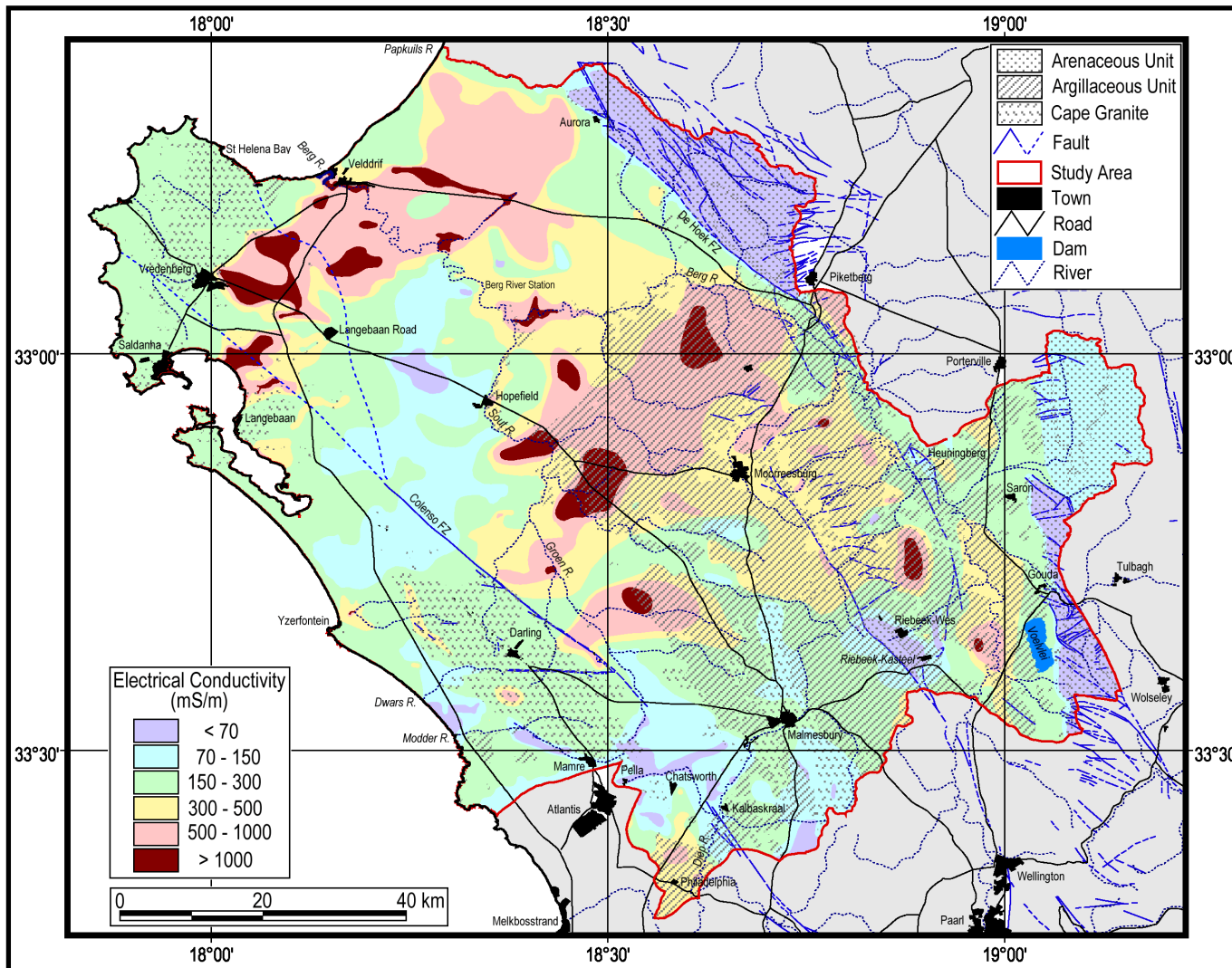


Figure 58: Groundwater Quality variability in the Study Area in terms of Electrical Conductivity (Woodford, et al., 2003).

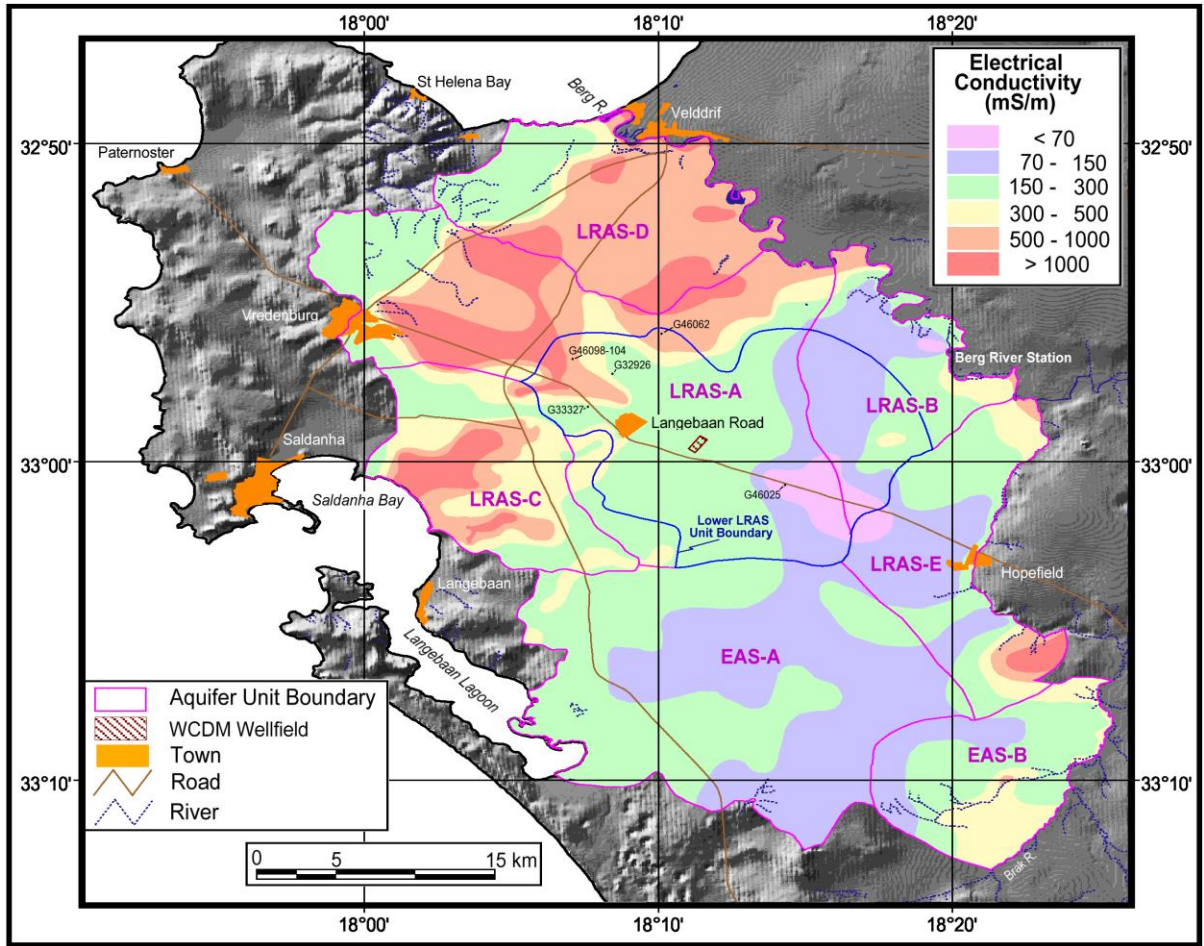


Figure 59: Electrical conductivity in mS/m as an indication of the water quality of the Langebaan Road and Elandsfontein aquifer units (Woodford 2004).

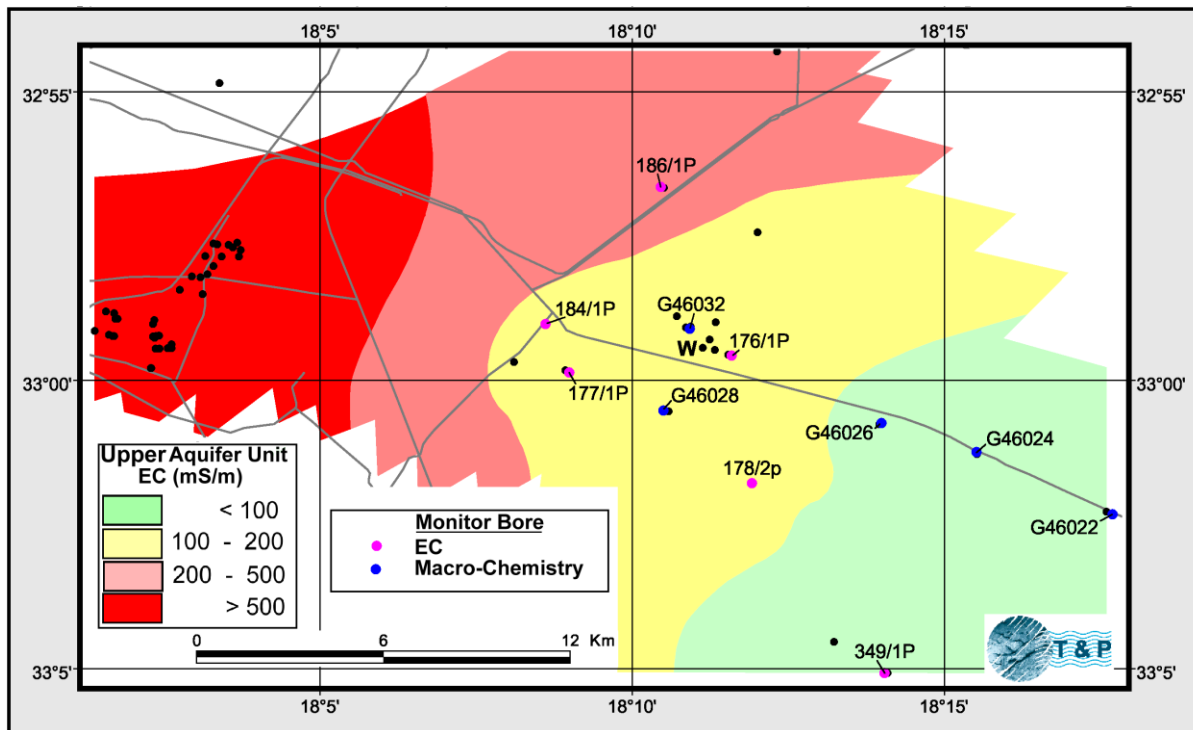


Figure 60: Water quality of the upper aquifer layer of the Langebaan Road aquifer unit (Woodford and Fortuin, 2003).

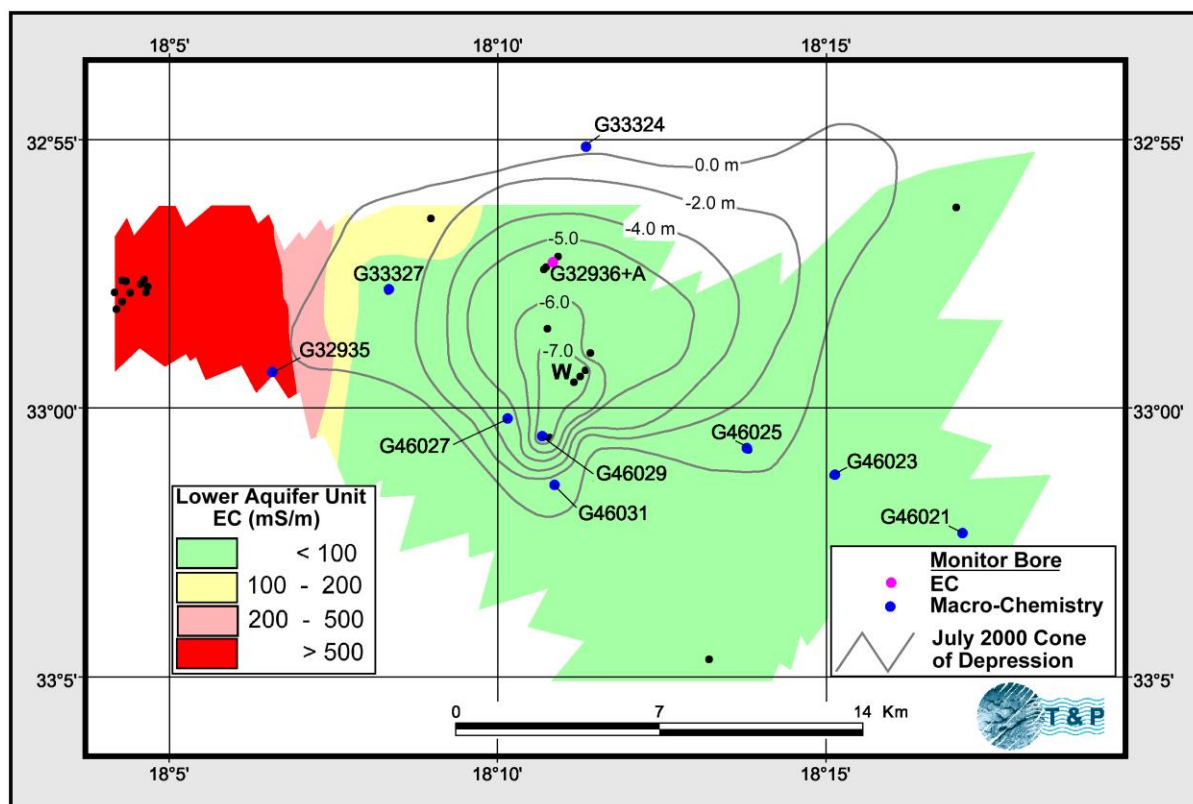


Figure 61: Water quality of the lower aquifer layer of the Langebaan Road aquifer unit (Woodford and Fortuin, 2003).

3.8.2.6 Protection

Groundwater was seen as a private entity under the Water Act of 1956 (Act 54 of 1956). The only way that groundwater could be protected, was through the declaration of a Subterranean Government Water Control Area. The Saldanha Subterranean Government Water Control Area which basically covered the Langebaan Road aquifer unit was declared in September 1976. Timmerman (1985c) proposed the expansion of this control area to include the Adamboerskraal, Elandsfontein and Grootwater aquifer units. The proposal was to include the three northern aquifer units into one, under the name Lower Berg River Subterranean Government Water Control area. The Grootwater aquifer unit would be a separate area. Baron (1990) did further work on the Grootwater aquifer unit and the area was declared in 1990 under the name Yzerfontein Subterranean Government Water Control area. Water allocations for the landowners on the Grootwater aquifer unit was promulgated in 1992. The formal declaration of the Lower Berg River Subterranean Government Water Control Area with its boundaries apparently never happened. The area where the groundwater would have been protected is shown in Figure 62.

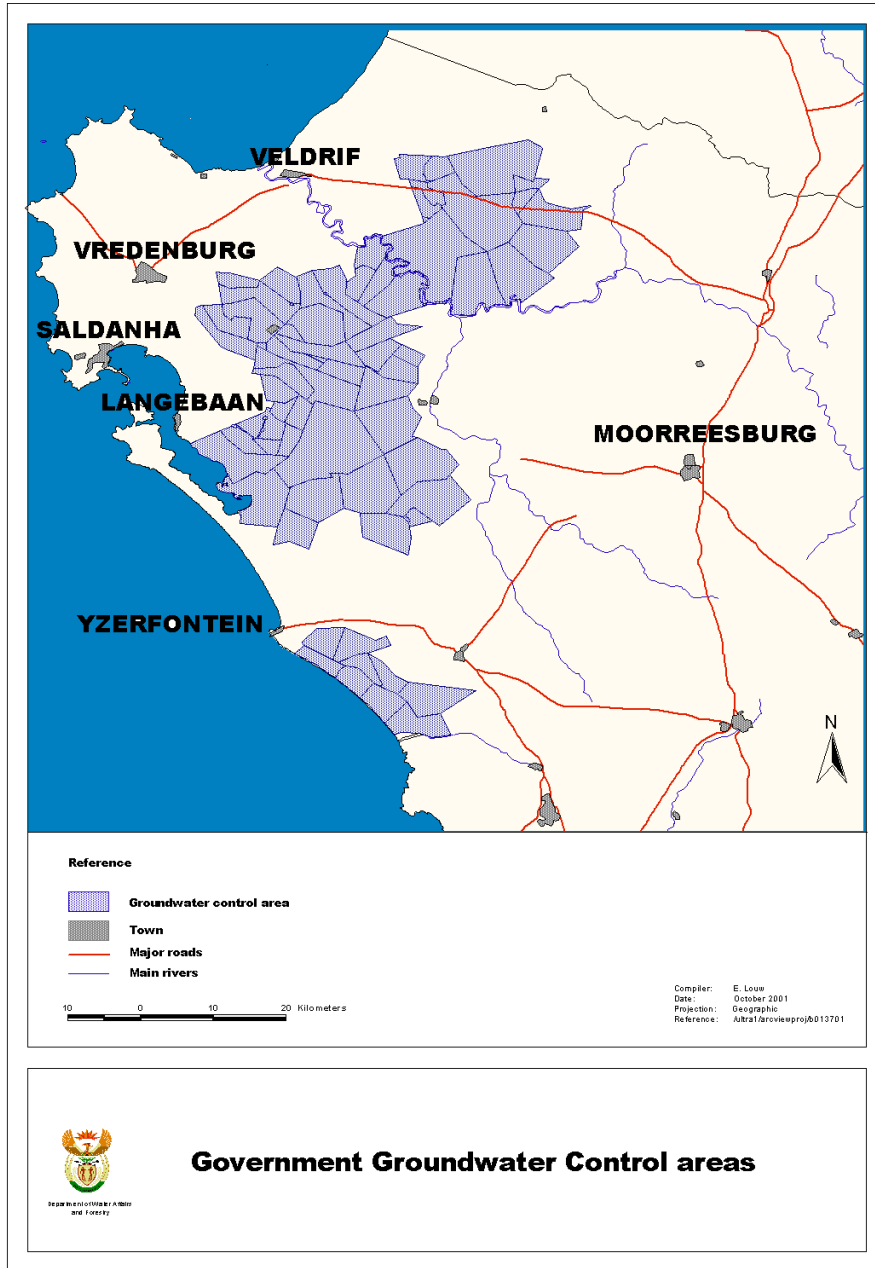


Figure 62: Lower Berg River and Yzerfontein Subterranean Government Water Control Areas.

The National Water Act of 1998 (Act 36 of 1998) replaced the Water Act of 1956. It included a number of tools for the protection of water resources, including groundwater. These tools and the legislation are discussed in Chapter 2.

3.8.3 Other water resources

Other water resources include **sea water** through desalination. This option has been investigated but put on the shelf for the time being due to the high cost (DWS, 2015; Smith, 2018). It is, however,

an option that will become more important in the future. The possibility also exists of desalinization of brackish groundwater, which makes the use of groundwater from parts of the Adamboerskraal aquifer unit a more viable option.

Storm water and **wastewater** are other options for additional water resources, but this would likely not make a big contribution to the water mix for a number of reasons. Storm water is the result of rainfall, and in a semi-arid region where rainfall is limited, there will not be a lot of storm water generated. It is, however, possible to make the most of the little that is available, even if it only reduces the use of potable use for gardening. Wastewater that is treated to potable standards is another option, but it is limited to the larger towns. It is currently being investigated for use by industries to reduce the reliance on the bulk system where potable water is being used for industrial processes (Smith, 2018). The **capturing of mist** may also provide some additional water.

3.9 Historical Conceptual Model

Timmerman and his contemporaries built on the work that was done by the Geological Survey of the Department of Mines in the early 1970s. Looking back at what they had achieved with the information and technology that had been available to them is astonishing. It provided a good basis on which to build.

It would seem that a lot of the drilling that was done in the time of Timmerman (1985b) was based on the findings of Smith (1982), at least for Elandsfontein and Langebaan Road. Most of the boreholes were sited along the palaeochannels as mapped by Smith in his basement contour map. Additional work such as pumping tests, down hole logging, granulometric logging, etc. were carried out during the project and recorded in a number of reports. The conceptual model that came out of the study was very detailed (See Figure 63).

The Timmerman conceptual model (K.M.G. Timmerman, 1985; Timmerman, 1985a; Timmerman 1985b; Timmerman, 1988) described the aquifer system to be linked to a series of palaeochannels, where the first deposits in the old river channels were fluvial in origin. The bedrock of the palaeochannels were from the shales of the Malmesbury Group or Cape Granite Suite. Thick layers of weathered clay were encountered during drilling and solid bedrock were very seldom encountered. This led to the conclusion that there would be no hydraulic interaction between the basement and the overlying aquifer layer. The Elandfontyn Formation of fluvial origin was deposited in the palaeochannels. This formation consisted of gravels, coarse sands, gradually grading upwards to end in clay and peat layers. This sequence was repeated twice, before the system changed into a lagoonal system with greater interaction with the sea. The Varswater Formation are from marine origin and contains a large amount of phosphate either as pellets or phosphatised shells. It is a finer sand with a relatively high clay content. Timmerman did not find the Saldanha Formation, as was described by Tankard (1975), between the Elandfontyn and Varswater Formations during his study. The Varswater Formation was divided into four layers,

based on their composition and the depositional environment, using the description of Rogers (1982):

- Calcareous Sand Member;
- Pelletal Phosphorite Member;
- Quartose Sand Member; and
- Shelly Gravel Member.

The Varswater Formation was followed by the Bredasdorp Formation (now known as the Sandveld Group), which was divided into five groups:

- Witzand Member and the Yzerfontein Member;
- Langebaan Limestone Member;
- Velddrift Member and the Milnerton Member;
- Springfontyn, Noordhoek and Papkuils Members; and
- Early Pleistocene deposits.

Detailed granulometric analysis were carried out as part of the study, with Figure 63 providing an example of the results of the analysis. This added detailed information on the porosity and conductivity of the aquifer system. Timmerman found that the clay layers thinned out towards the edges of the palaeochannels and were often absent.

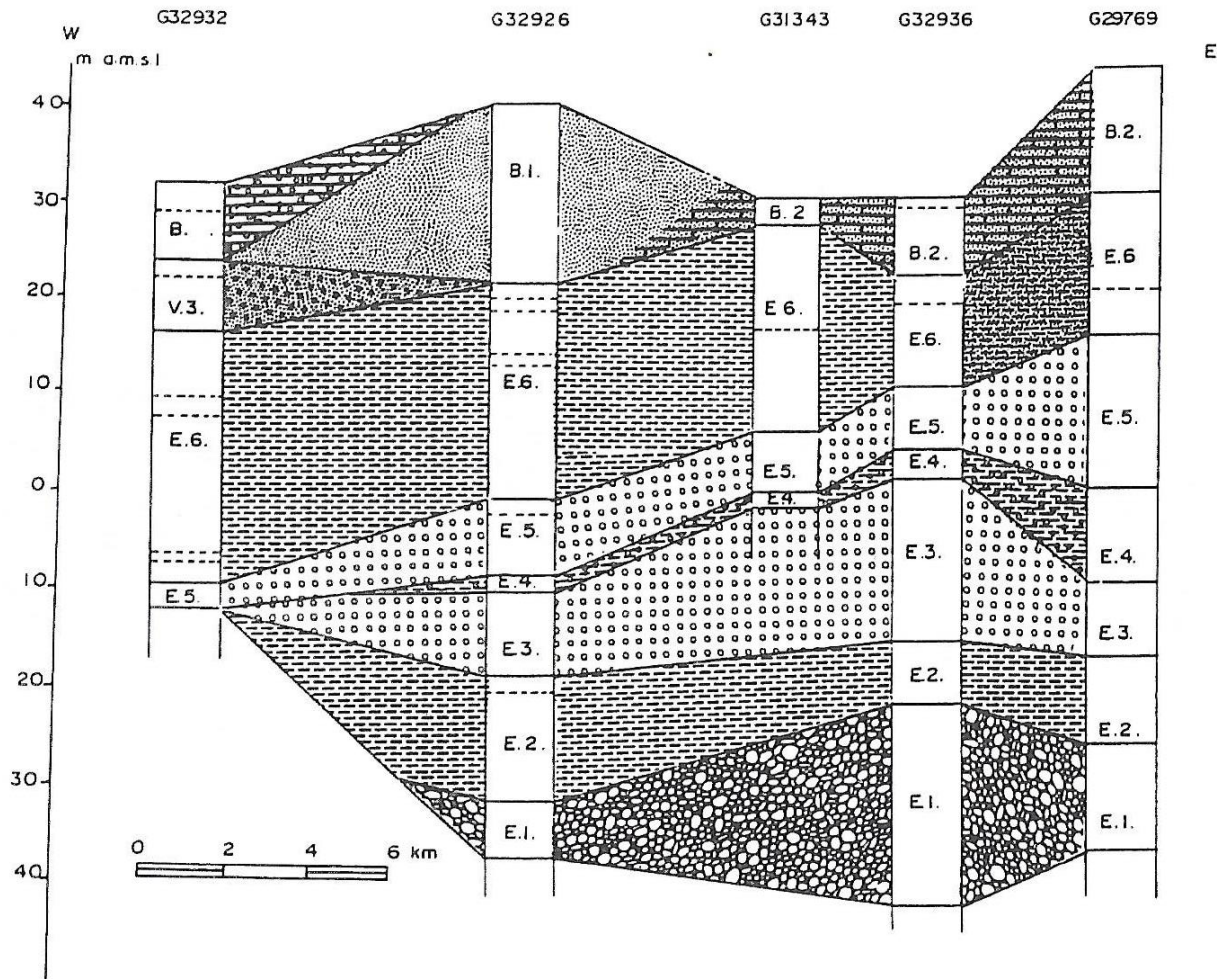


Figure 63: Lithostratigraphical profile showing the sedimentology of the aquifer system (Timmerman, 1988). The Adamboerskraal aquifer unit was studied by K.M.G. Timmerman (1985) and three palaeochannels were found. It was thought to be associated with the Kuilders River, the Berg River and the Papkuils River. Timmerman (1988) suggests that the two southern palaeochannels may both have been associated with the Berg River. One of the Adamboerskraal palaeochannels are connected to the Langebaan Road palaeochannel underneath the current Berg River channel. The sedimentology / stratigraphic sequence of the Adamboerskraal aquifer unit correlates with that of the Langebaan Road aquifer unit.

The Langebaan Road palaeochannel runs from the Berg River towards Saldanha Bay (Figure 64). The Elandsfontein palaeochannel runs from the Farm Sonquasfontein just north of Darling in a northwesterly direction to the Farm Elandsfontein (sometimes also spelled Elandsfontyn), where it changes to a southwesterly direction towards Geelbek at the Langebaan Lagoon. According to the conceptual model proposed by Timmerman, there is a no-flow boundary between the Langebaan Road aquifer unit and the Elandsfontein aquifer unit (Figure 64). The reasoning behind

this has to do with the geohydrological concept that a topographical high denotes a no-flow boundary (watershed) and the fact that there is a basement high between the two palaeochannels. The map seems to indicate that there is a section in the basement high between the two palaeochannels that are below sea-level, that can potentially indicate a link between the lower aquifer layers of the two aquifer units.

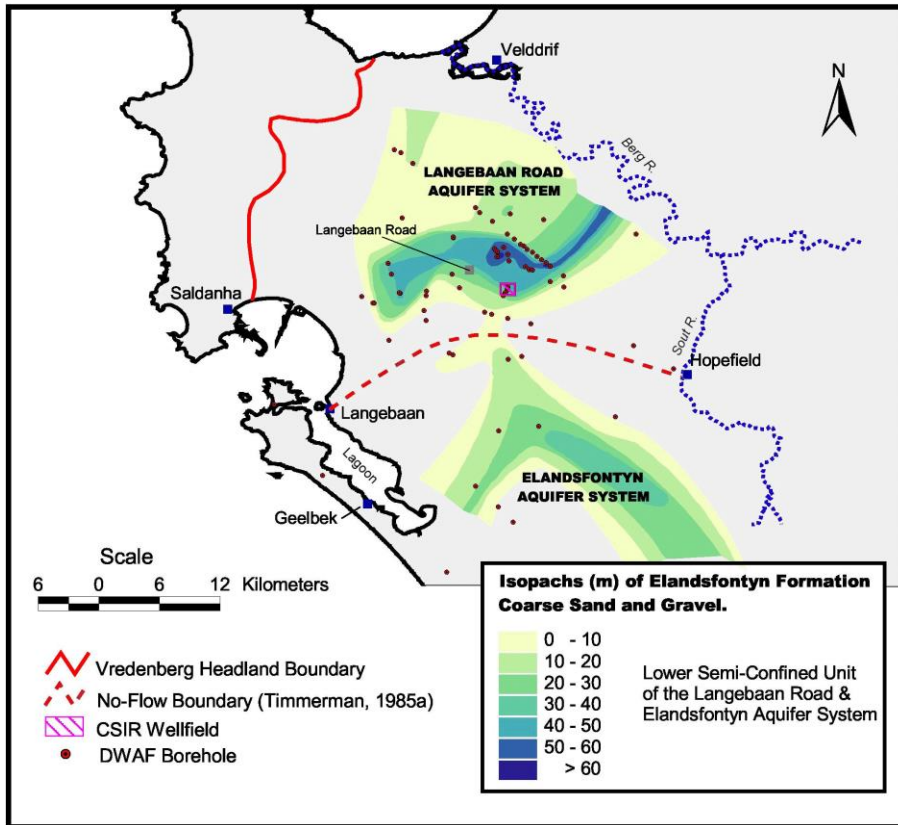


Figure 64: Thickness of the Elandsfontyn Formation coarse sand and gravel, indicating the base of the Langebaan Road and Elandsfontein aquifer units (Woodford and Fortuin, 2003; after Timmerman, 1985a).

Figure 65 shows the cross-section of the conceptual model developed by Timmerman (1988), indicating the recharge zone, the basement high and the no-flow boundary between the Langebaan Road and Elandsfontein aquifer units. The no-flow boundary is only between the palaeochannels and thus the Elandsfontyn Formation, as the rest of the cenozoic deposits that make up the two aquifer units are hydraulically linked. The confining layer between the upper and lower aquifer layers in the Langebaan Road aquifer unit was the reason given for the artesian conditions at certain parts of the of the aquifer unit. The artesian conditions usually occur to the northwest of the Langebaan Road wellfield, but abstraction has affected it greatly.

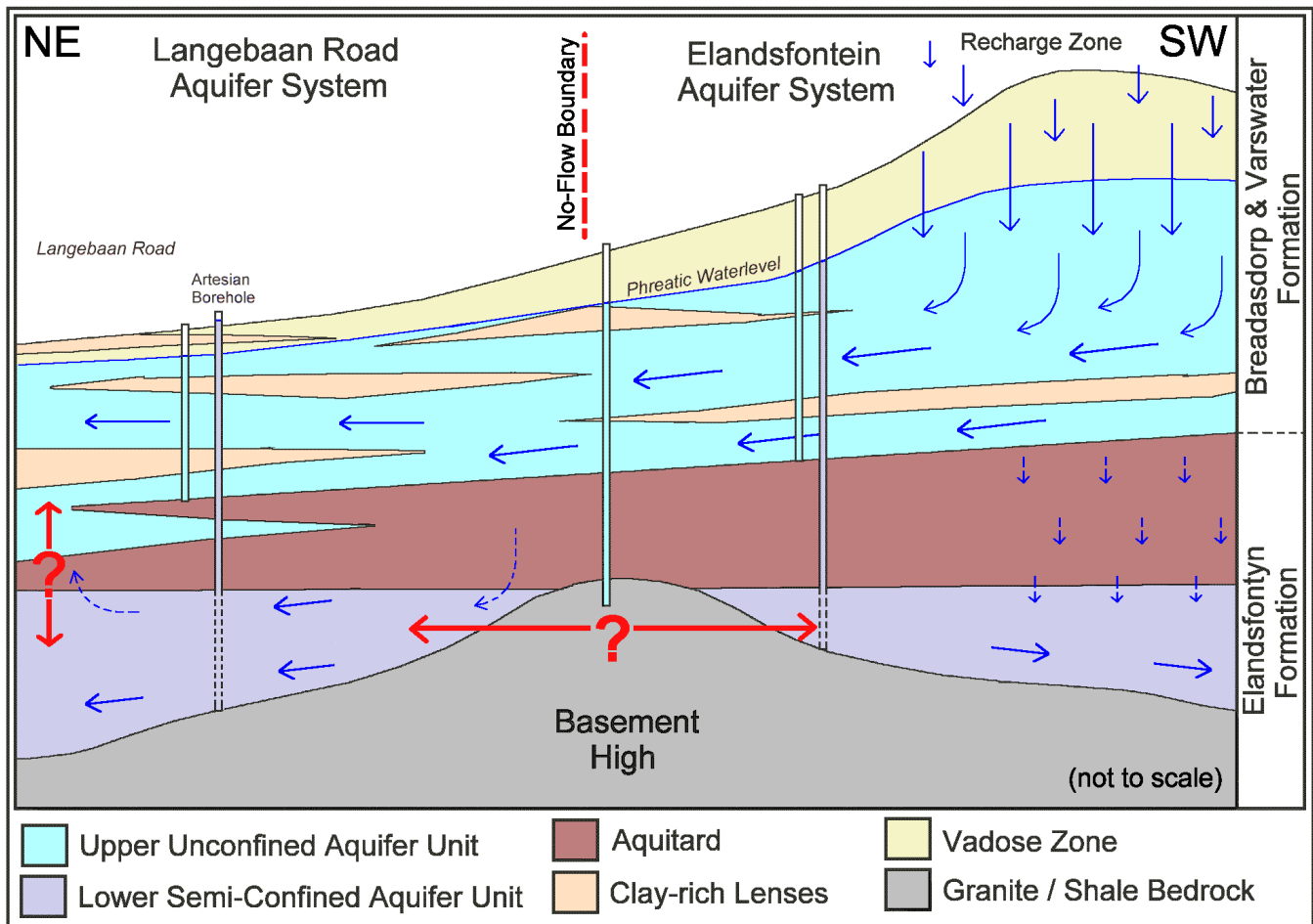


Figure 65: Cross-section of the conceptual model of the aquifer system (Woodford and Fortuin, 2003; Woodford, et al., 2003).

The Grootwater aquifer unit consisted of three palaeochannels that coincides with the current Modder River, Dwars River south and Dwars River north. It was separated from the system above it by a basement high in the geology. The area north of the Grootwater aquifer unit was not properly investigated in the time of Timmerman as a result of drilling difficulties associated with the calcrete. The Grootwater aquifer unit was thus seen as separate from the rest of the Lower Berg River aquifer system hydraulically and geographically.

Figure 66 provides an indication of the area that Timmerman investigated and gives a delineation of the aquifer units. Note the no-flow boundaries indicated on the map between the different aquifer units. The understanding that Timmerman gained from his investigation was then used to indicate the areas that would be best suited for the development of wellfields. These are often mistaken in literature as the extent of the aquifer units. He studied only the northern three aquifer units in more detail for his thesis (Timmerman, 1988).

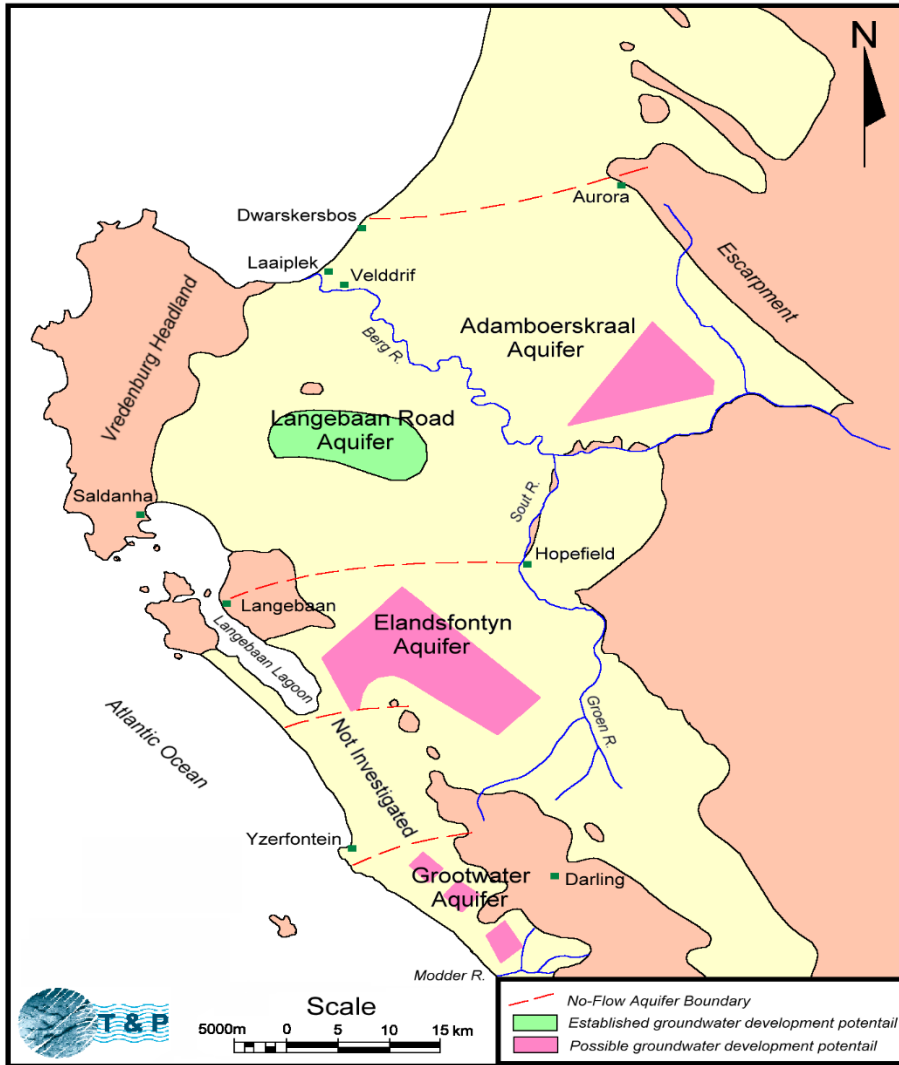


Figure 66: Map showing the study area (Timmerman, 1985b; as adapted by Woodford and Fortuin, 2003).

The conceptual model developed by Timmerman provided the basis for the development of the Langebaan Road wellfield. The no-flow boundary between the two palaeochannels were used to allay fears that the abstraction would impact the Langebaan Lagoon and its sensitive ecosystem.

Woodford and Fortuin (2003) was the first to question the conceptual model with its no-flow boundaries between the Langebaan Road and Elandfontein aquifer units. This came as a result of his work for the West Coast District Municipality (WCDM) on the effects of the abstraction at the Langebaan Road wellfield. Figure 56 shows the contour lines for the water levels in the lower aquifer layer (Elandsfontyn Formation) after a number of years of abstraction from the Langebaan Road wellfield, while Figure 67 shows the water levels in piezometer 1 of G33320 compared to the abstraction. The impact of the abstraction at the wellfield can be clearly seen in the Langebaan Road aquifer unit, but it stretched wider than expected. It also seemed to impact dug wells and boreholes in the upper aquifer layer, which was not expected. The drawdown as predicted to be 5m below the static watertable (Weaver, et al., 1997), but it stabilized at 11m below the static water

levels. The impact towards the Elandsfontein aquifer unit was not expected either, with a time lag between one year and three in some cases. This can be seen with the contour line including borehole G33320, with is in the northern part of the Elandsfontein aquifer unit. Woodford and Fortuin (2003) seems to link the possible interaction between the two aquifer units to the inferred shale-granite contact that underlies the area.

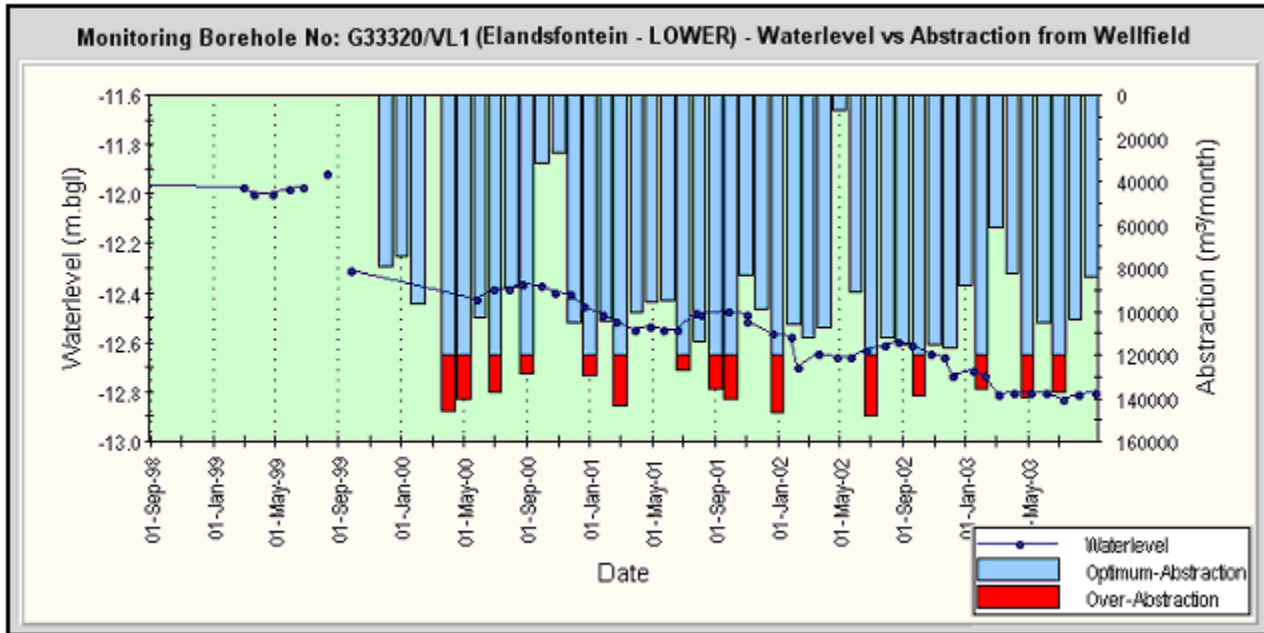


Figure 67: Water level fluctuations G33320-VL1 versus Abstraction in the WCDM Wellfield (Woodford and Fortuin, 2003).

Woodford and Fortuin (2003) used the information gained from the analysis of water levels in response to the abstraction at the Langebaan Road wellfield to refine the conceptual model of the Langebaan Road aquifer as well. Borehole logs of G33326 showed well developed Elandsfontyn deposits (Timmerman, 1988) and maps of the Elandsfontyn clay layer areas very thin (approximately 5m or less; See Figure 69). Figure 68[A] shows the influence of abstraction from the Langebaan Road wellfield on the water levels of the borehole from November 1999. This caused the extension of the boundary of the lower aquifer layer of the Langebaan Road aquifer unit further towards the Berg River in this area during this investigation. It should be noted that the water level does not always recover during the winter rainy season, like in July 2000 (Figure 68[B]). The conclusion was that the Berg River may contribute significantly to aquifer recharge. It also shows that the clay layer is also not present in all cases, providing a separation between the upper and lower aquifer layers.

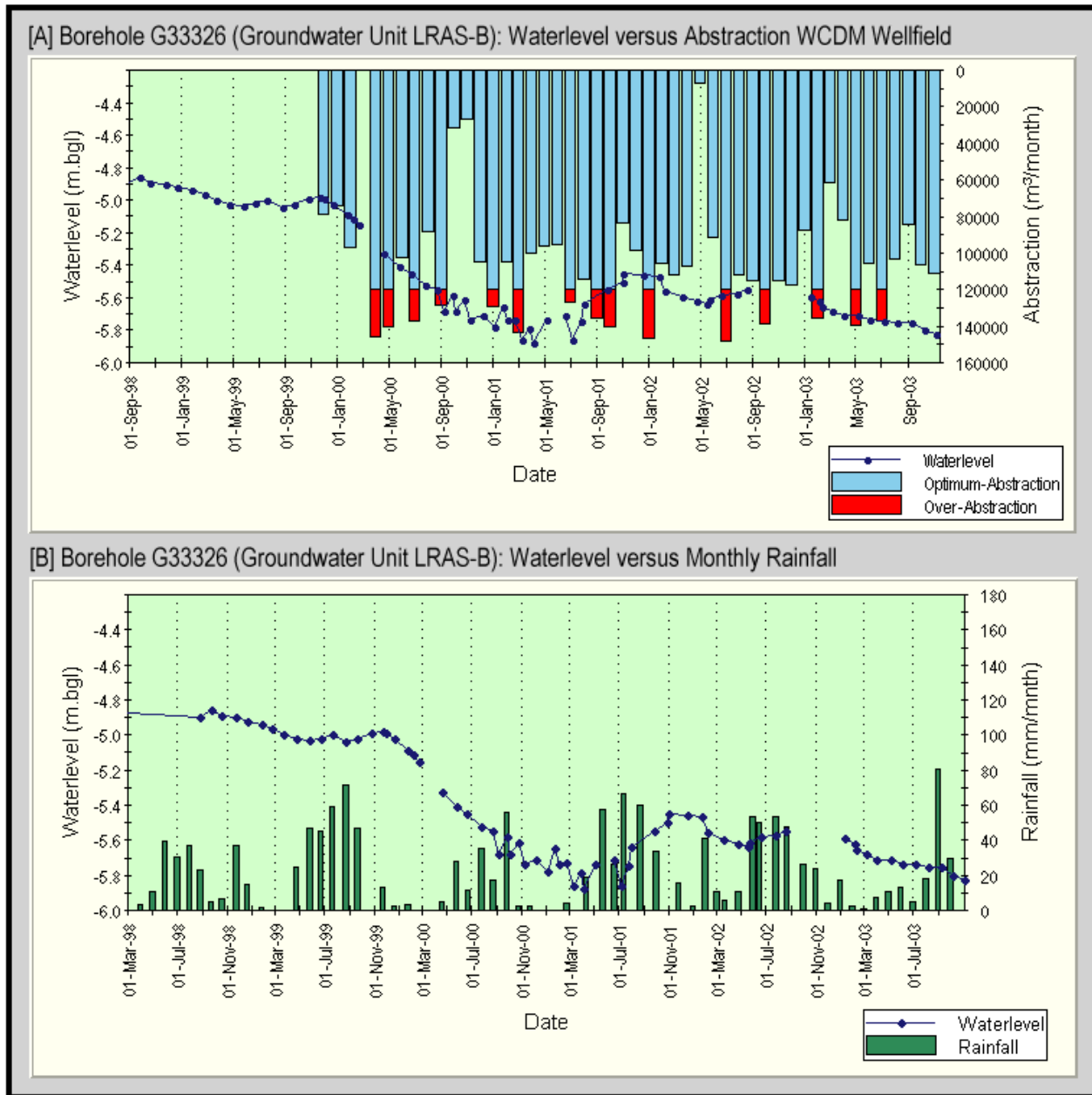


Figure 68: Water level fluctuations in Borehole G33326 versus [A] Wellfield Abstraction and [B] Monthly Rainfall (Woodford and Fortuin, 2003).

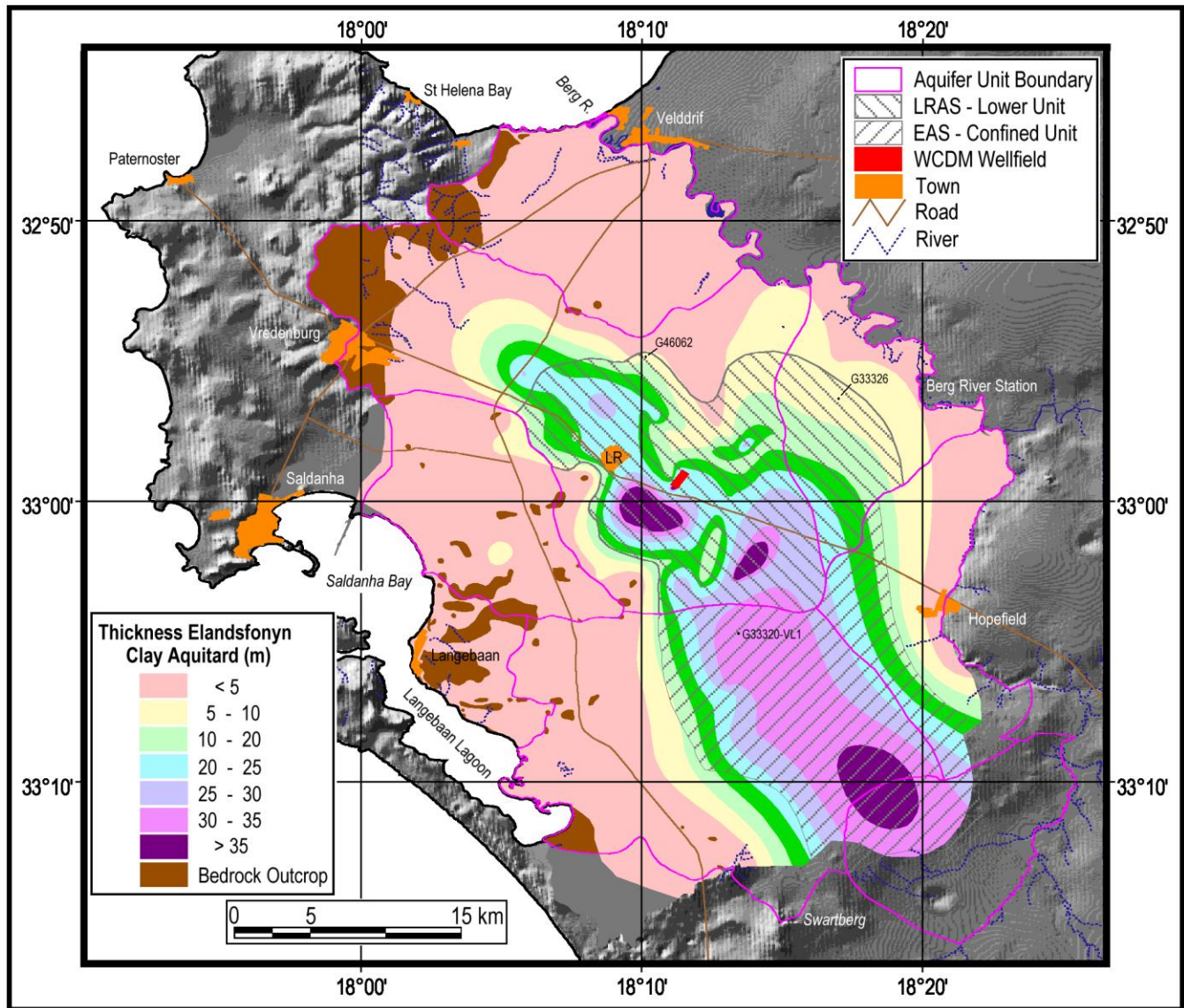


Figure 69: Isopachs of the Elandsfontyn Clay Aquitard (Woodford and Fortuin, 2003).

The Berg WAAS study (DWAF, 2008) still uses the idea of a no-flow boundary proposed by Timmerman, but the line has been adjusted (Figure 70). The bedrock contours have also been adjusted, and no longer shows a link between the lower aquifer layers of the two aquifer units. The link between the Adamboerskraal aquifer unit and the Langebaan Road aquifer unit have been discounted based on borehole data that did not show the link between the two palaeochannels. The conceptual model used for the study includes the work done by De la Cruz (1978) and De la Cruz and Du Plessis (1981) in Saldanha Bay. Based on this information the palaeochannels are extended into Saldanha Bay and underneath Langebaan Lagoon and Sixteen Mile Beach to the ocean. The conceptual model relied heavily on the NGDB data (now NGA).

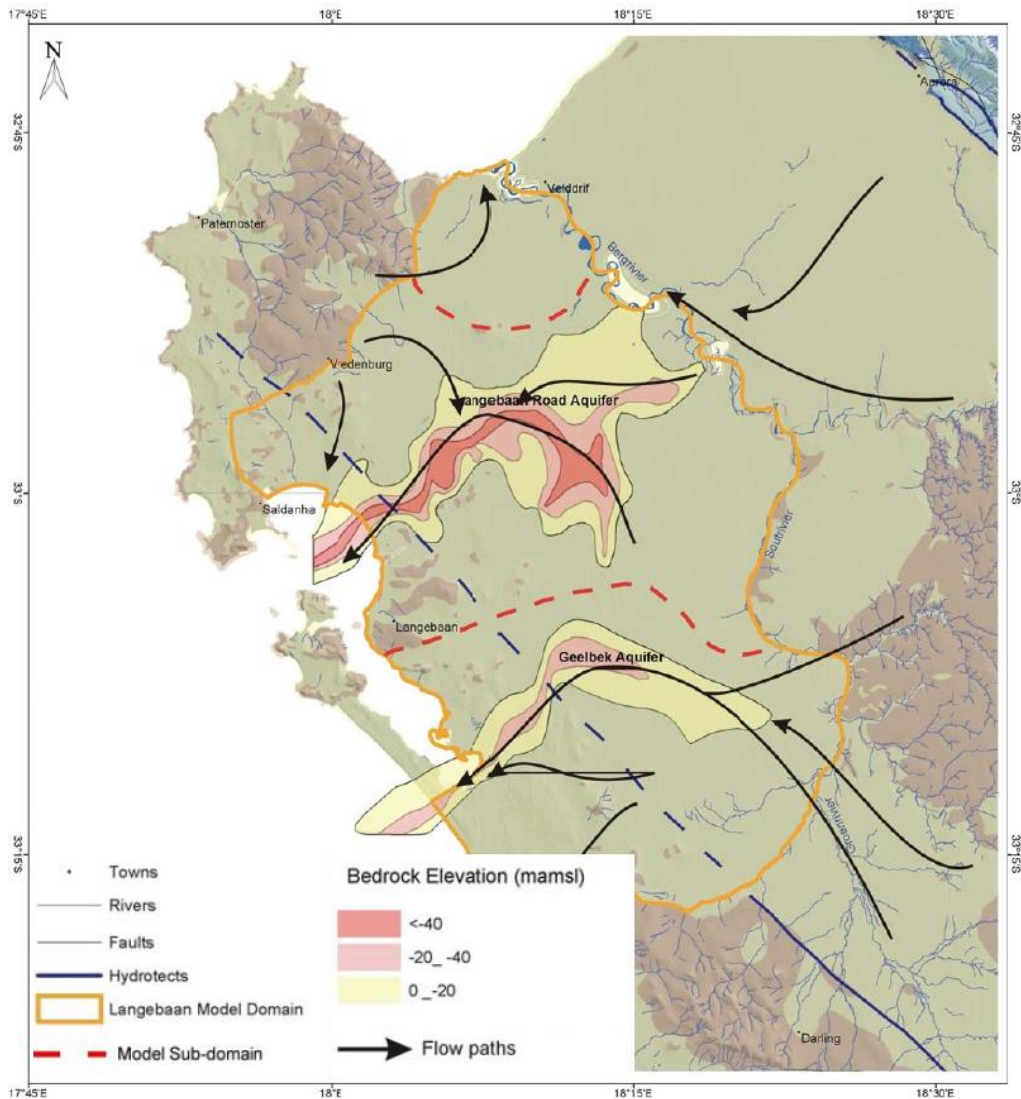


Figure 70: Conceptual model of groundwater flow in the Langebaan Road and Elandsfontein aquifer units (DWAf, 2008).

The CSIR was contracted by DWAf to do the first artificial recharge tests at the Langebaan Road wellfield in the winter of 2008 and 2009. Part of their conceptual model explaining recharge to the Langebaan Road aquifer unit is shown in Figure 71. The artificial recharge was not as successful as hoped and it showed that there were certain points of the original Timmerman conceptual model that needed to be re-evaluated (Tredoux and Engelbrecht, 2009).

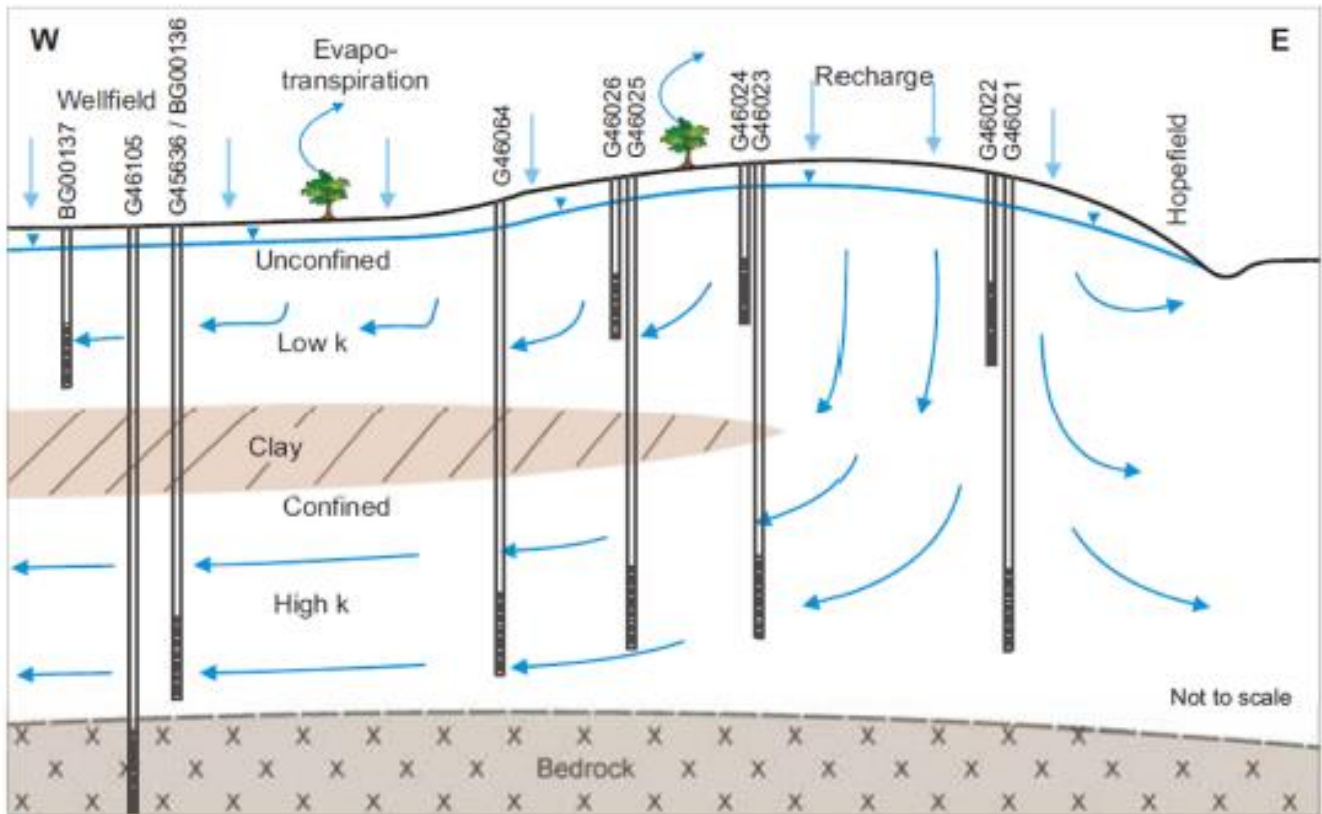


Figure 71: Conceptual model of the recharge area (Tredoux and Engelbrecht, 2009).

Seyler, et al. (2016) revised conceptual model for the Lower Berg River Aquifer System by using the basement contours of Roberts and Siegfried (2014), with modifications based on the NGA data. It found that the basement high was absent or localized (Woodford, 2009), and that a palaeochannel may have developed along the shale-granite contact. The clay layers may not be continuous throughout the aquifer system, as it seemed that the clay layer has eroded along the lower reaches of the proto-Berg River. This would place the lower and upper aquifer layers in direct hydraulic contact. The continuous channel under Saldanha Bay and Langebaan were included. There is also hydraulic connectivity between the basement and the overlying Elandsfontyn Formation (Woodford, 2009). This makes it possible that recharge may be taking place at a distance through the faults and contact zones of the basement. The Lower Berg River aquifer system was accepted to be one hydraulically linked groundwater resource unit (GRU).

Conceptual models should develop over time as more becomes known about the aquifer system, with regular reviews and updates. A summary of this progression with some of the highlights is shown in Figure 72.

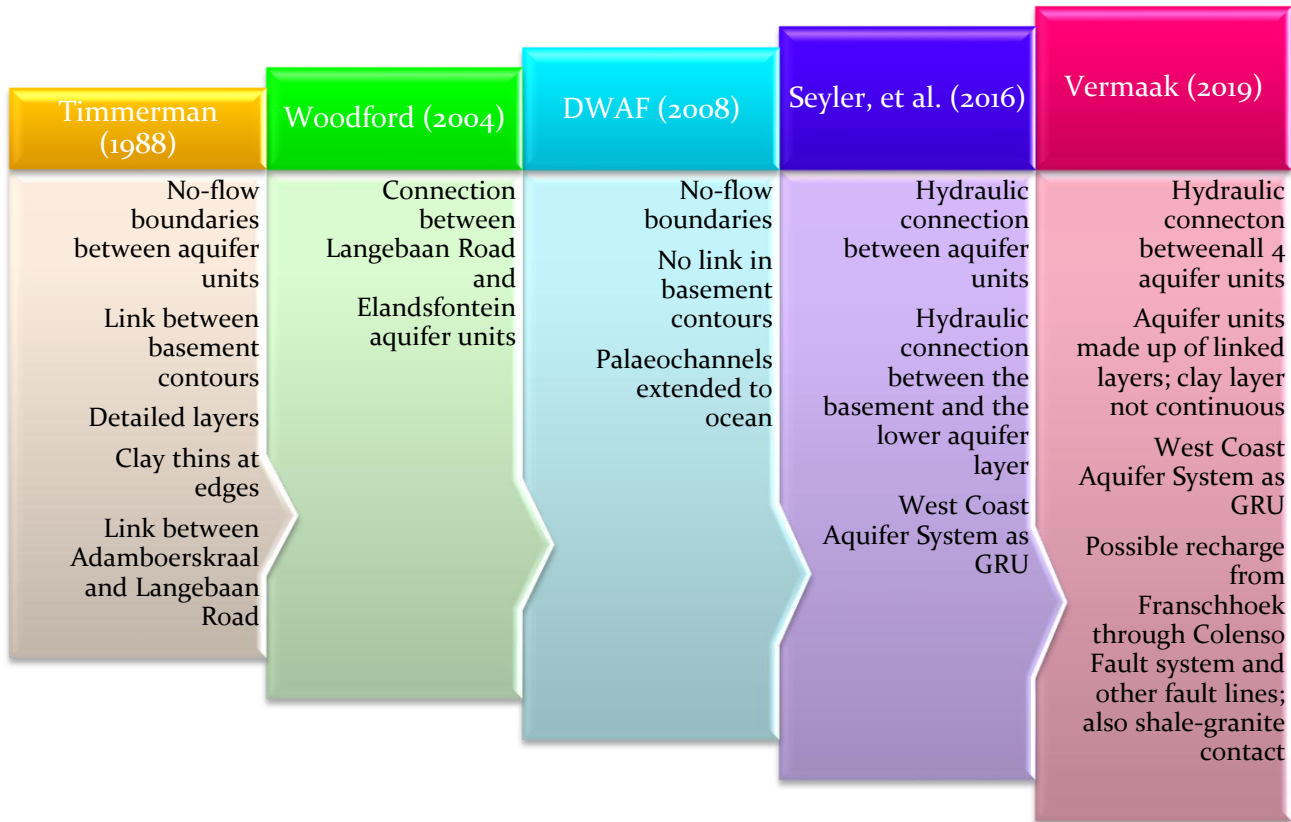


Figure 72: Development of conceptual models over the years.

3.10 Summary

The information presented in this chapter provides window into the parts that make up a very interesting, but complex groundwater system. The initial work was very detailed and provided the information on which future studies could build. It also showed that there were still gaps in the understanding of the aquifer system, leaving room for future investigations Chapter 4 will look at more recent information, based on the monitoring data and personal observations. It will present the information on which the latest version of the conceptual model (Chapter 5) is based.

Chapter 4: Geohydrological Characteristics



G46088 on the Farm Lekkerwater (28 August 2017)

In most cases the conceptual model is built after the geohydrological investigation and initial measurements. The first geohydrological investigations for the study area were done in the early 1970s and almost five decades for monitoring data has been collected. The monitoring data provides a window into the Lower Berg River aquifer system. More than 200 geosites formed part of the monitoring. The monitoring data and personal observations were used in the construction of a conceptual model. The conceptual model was also revised and calibrated as it were with the monitoring data. Only initial statistical analysis has been done with only a small portion of it presented in this chapter. The information will contribute to the first objective in presenting the data on which the conceptual model is based.

The chapter will begin by assessing rainfall data, water level data and the correlation between the two. It will also evaluate the effects of the abstraction at the wellfield and the MAR tests on the water levels of the aquifer system, as well as the water quality and how it correlates with the geology of the area. The chapter will end with the discharge of groundwater from the aquifer

system and a brief look at the groundwater dependent ecosystems associated with the Lower Berg River aquifer system.

4.1 Rainfall

Rainfall is the input as it were into the hydrological cycle, thus the recharge to the groundwater systems. Rainfall measurements has traditionally been used as the basis of recharge calculations where the volume of recharge to groundwater has been calculated as percentage of rainfall. Rainfall has changed over time and is highly seasonal (Adams, 2019). Rainfall intensity and magnitude vary greatly from place to place and is influenced by different topographical and meteorological conditions (Yesertener, 2008). The direct observation of precipitation seldom explains the variation in groundwater levels (Smail, et al., 2019), as there may be a lag in the response, or various sources of recharge may influence the groundwater system. Recharge therefore a generalization that can potentially be used incorrectly. It should therefore not be seen as a static number that can be used forever. It should ideally be recalculated for each season to give correct estimates. Rainfall (also called precipitation) is usually the largest part of the water budget (Smail, et al., 2019).

Rainfall for the study area was measured with cumulative rainfall collectors that is equipped with a Perspex measuring tube and OTT Thalimedes for continuous recording of data. The rain gauge was designed by the Department of Water Affairs, Directorate Geohydrology (Havenga, 2010) and the idea behind the design is to be able to collect rainfall samples that can be used for chemical and isotope analysis, to be used in recharge estimations. The Thalimedes recorded hourly readings that are then processed using Hydras3 (OTT HydroMet, 1991). The data then had to recalculate to get monthly values, to be able to compare with data from SAWS and with water levels. Some of rainfall data was collected by farmers and other private citizens. Rainfall records from South African Weather Services were also used. Bar graphs with plotted with the time series rainfall records using Excel.

The cumulative deviation from mean (CDM) were calculated and plotted on the secondary axis on the same graph. CDM is a simple arithmetic technique used in the evaluation of rainfall (Yesertner, 2008). Previous applications of this technique include determining the relation between the cumulative departure from average rainfall and the flow of a karst spring in the Moapa Valley, Nevada (Eakin, 1964), an extensive analysis of rainfall variation in South Africa by Temperley (1980) and the work of Boehmer (1998) that show that natural groundwater level fluctuations near Colesberg in the Karoo, South Africa correlates with cumulative departure graphs of rainfall. The method was also applied in an extensive analysis of rainfall variation from the Lower Dalaman River Basin (Yesertener, 1986) and Upper Ermenek River Basin (Yesertener, 1995) in Turkey. This analysis showed a close relationship between the CDM plots of rainfall and the natural water level fluctuations in karst springs in western and southern Turkey. The technique was applied to 110 groundwater hydrographs for boreholes in the Gngangara Groundwater Mound, just outside Perth, Australia to identify the potential impacts of land and water use on groundwater levels in the area (Yesterner, 2008). Ferdosian and McCarron (2001)

developed a software programme called HARTT to estimate trends in groundwater levels based on the technique. It also uses multiple regression analysis to separate the effects of atypical rainfall events from underlying time trends and the lag between rainfall and its impact on groundwater levels.

Smail, et al. (2019) tested the used CDM to predict time series water levels where rainfall data was available, but groundwater level measurements absent. The outcomes of the study were that the CDM technique can be used to correlate water levels with rainfall and to identify factors that may be interfering with or confounding the connection between proximate precipitation and measured groundwater levels. Emelyanova, et al. (2013) used the CDM technique to determine whether it would be possible to project groundwater levels under future climate conditions. The CDM technique has been used extensively to predict groundwater levels from rainfall (Sophocleous, 1991; Butterworth, et al., 1999; Lote-Tree Software, 2001; Ferdowsian, et al, 2001; Xu and van Tonder, 2001; Yesertener, 2005; 2008; Golder Associates, 2008; Emelyanova, et al., 2013). Xu and van Tonder (2001) improved the algorithm using it for recharge estimations in the Grootfontein and Karoo aquifers in South Africa. Long-term trends in groundwater levels in an experimental catchment in Zimbabwe, together with CDM of rainfall records were used to develop guidelines for groundwater schemes to ensure safe long-term yields and to predict future stress on groundwater resources during periods of low rainfall (Emelanova, et al., 2013).

The cumulative deviation from mean uses concepts that are similar to the rescaled range method, described by Hurst, et al. (1965). It is based on the estimation of cumulative departures of influx of an ideal reservoir from an annual mean value over a period of monitoring. The cumulative deviation from mean is calculated in the following way (Yesertener, 2008):

- determine the average of the rainfall measurements over a defined period;
- determine the difference between the average and the actual measurement of the same defined period to find the deviation from the mean;
- the deviations are then plotted cumulatively in a graph, providing a time series of the net surplus or deficit in precipitation from the mean;
- periods of above mean rainfall show an upward trending graph (wet cycle), while rainfall below the mean is downward trending (dry cycle).

It is necessary to have complete records and a good network of rain gauges to use the rainfall data for any hydrological evaluation. It is possible to use regression analysis or other classical methods to estimate essential missing data to enable the evaluation of groundwater level changes (Yesertener, 2002; 2008). Smail, et al. (2019) found a relatively high correlation between the CDM of rainfall and groundwater levels. Borehole depth and casing had a weak, but statistically significant effect on the correlation between the CDM curve and water levels, while the correlation was independent of aquifer classification and location in a groundwater system. An optimal length of the data record added to the level of correlation.

Yesertener (2008) used the CDM to determine wet and dry cycles and to compare the resultant curve with water levels measured in boreholes in the Gngangara Groundwater Mound. Declining trends were correlated with abstraction from both the confined and the unconfined aquifers, evapotranspiration from pine plantations and decreases in rainfall, while rising trends were attributed to increasing rainfall, clearing of vegetation (both natural and pine plantations), bushfires and thinning of the pine trees. It is thus clear from the analysis of the data for Gngangara Groundwater Mound that reduced rainfall and groundwater abstraction were the major causes of declining trends, with climate, especially changes in rainfall, land use changes and groundwater abstraction were the major factors that affected groundwater levels.

Yesertener (2008) also found that if the CDM for rainfall was plotted with water levels affected by abstraction; it would be possible to determine whether the abstraction is sustainable. If two curves fit, the abstraction rate was seen as sustainable. When the water levels were lower than CDM, it gave an indication that the abstraction not sustainable, and the possibility existed of dewatering the aquifer. The method was tested on data for Grootwater aquifer (Vermaak, et al., 2017) using rainfall measured at Jakkalsfontein and the data for borehole G33333. The borehole has two active piezometers in a semi-confined system. It was initially found that the curves did not fit at all and the conclusion was reached that this method apparently only works for unconfined systems (Vermaak, et al., 2017).

The CDM method assumes that the cumulative rain departures from the mean annual rainfall record correlate with the groundwater level changes (Butterworth, et al., 1999; Xu and van Tonder, 2001; Emelyanova, et al., 2013). Smail, et al. (2019) list a number of factors that may affect the accuracy of the method. They found that although CDM curves often correlate well with observed water levels in boreholes, the application may be limited by a critical sensitivity to the period of the record that is used to calculate the mean. This may lead to several analytically awkward outcomes, such as the fact that the CDM series will begin and end at zero if the period over which the evaluation is done is the same as that used to calculate the mean. The possibility also exists that extreme events, such as heavy rainfall or drought near the beginning of the time series may affect the results of the technique. This is further complicated by the fact that renewed monitoring efforts often coincide with hydraulic droughts (Hayes, et al., 2012). Where monitoring boreholes were installed in confined systems where the aquitard disconnects the aquifer from the proximate precipitation, it is difficult to get a correlation between the CDM for rainfall and water levels. It is also possible that the location of the monitoring borehole may amplify the response of the aquifer to precipitation and that proximity to a river may cause 'noise' in the groundwater levels in response to changes in river stage (Smail, et al., 2019). Yesertener (2008), however, found that the location of the borehole does not greatly contribute to the accuracy of the method.

Limitations of the CDM methodology include the fact that it may only be applicable to boreholes in unconfined aquifers that receive direct recharge. There is also a question about the application of the method on boreholes that are in close proximity to areas where significant groundwater-surface water interaction takes place, or in areas where the water table is very shallow or very deep

(Ferdowsian, et al., 2001; Xu and van Tonder, 2001). It also does not account for changes in land cover and abstraction of groundwater, which is why Yesertener (2008) added additional components to the basic method to be able to account for these factors. It is also possible to misapply the method if an atypical period of rainfall is chosen for the analysis (Weber and Steward, 2004).

Limitations of the cumulative rainfall departure from mean (CRD) recharge estimation method will also apply to the CDM method. Bredenkamp, et al (1995) have demonstrated that natural water levels will continue to rise even if the CDM curve has a negative slope as long as there is a surplus of recharge over the discharge of an aquifer. Xu and van Tonder (2001) identified two additional limitations. Most of the South African aquifers are fractured, with small storativities. This makes them very sensitive to recharge and reduces the accuracy of the method. The second factor that limits the accuracy of the CRD and thus the CDM method is the depth to water table. The accuracy of the method below 50m below ground level should be applied with time lags, as the water level fails to respond to rainfall signals at this depth. It is thus also possible that the accuracy of the method could be affected by confining layers as well.

Figure 73 shows the location of a number of rainfall stations in the study area, with Table 19 giving a summary of data that was available for the analysis. BG00071-RF, BG00074-RF, G33323-RF, G46024-RF, G46059-RF, G46092-RF, G46105-RF and G10K1 are DWS cumulative rain gauges. Arnelia, Langrietvlei, Kleinklipfontein and Jakkalsfontein are private rainfall stations, while the rest are SAWS stations.

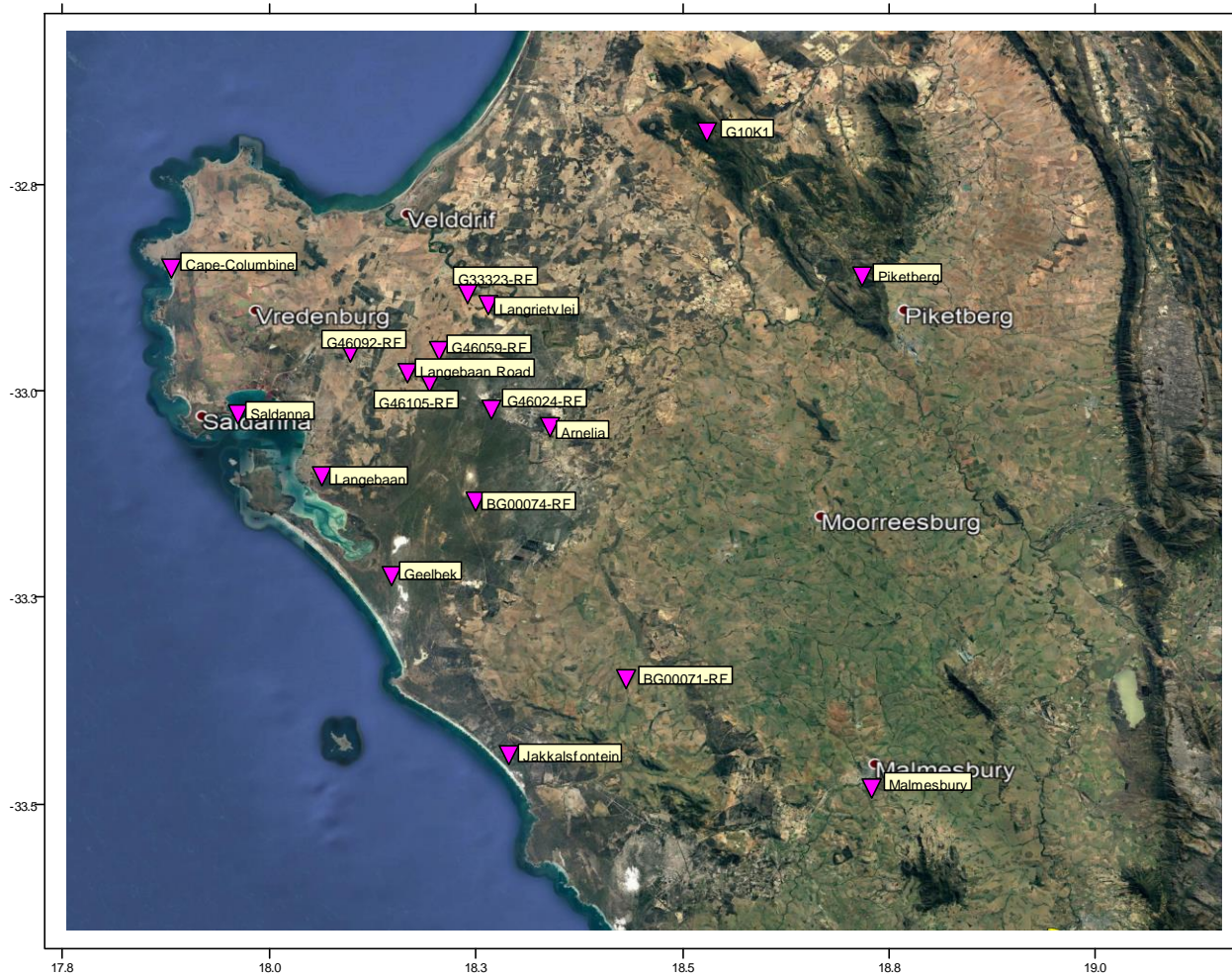


Figure 73: Satellite image showing the location of the rainfall stations (WISH; Lukas, 2012).

Figure 74 shows the data record for a number of the rain gauges with the cumulative deviation from mean curves. The rainfall has a definite seasonal pattern, with the highest rainfall in the winter months (usually from April to October). It is also clear that the volume of rainfall recorded for each station is different. Rainfall is dependent on a number of characteristics, which includes topography (orographic rainfall), distance from the coast, whether it is a mountain range or a single mountain, wind direction and speed, and temperature (Vermaak and De Haast, 2013). Rainfall may vary over short distances. The CDM curves show similar cyclical patterns, especially for rainfall stations in the same area and topography. The greater the difference in the setting of the rainfall station, the smaller is the similarity in the CDM patterns. Most of the analysis of these CDM patterns show a 10-year cycle, that usually includes three to five wet years and five to seven drier years (Vermaak, et al., 2015). There are exceptions to this pattern, but it was found in most cases studied in the Berg River area. Previous analysis gave an indication that the 7th year of a decade (or close to it) was usually linked to higher rainfall, that resulted in flooding. The maximum rainfall measurements in Table 19 seems to corroborate that, since the highest rainfall was measured in 1977, 1987, 1996, 2007 for some of the rainfall stations.

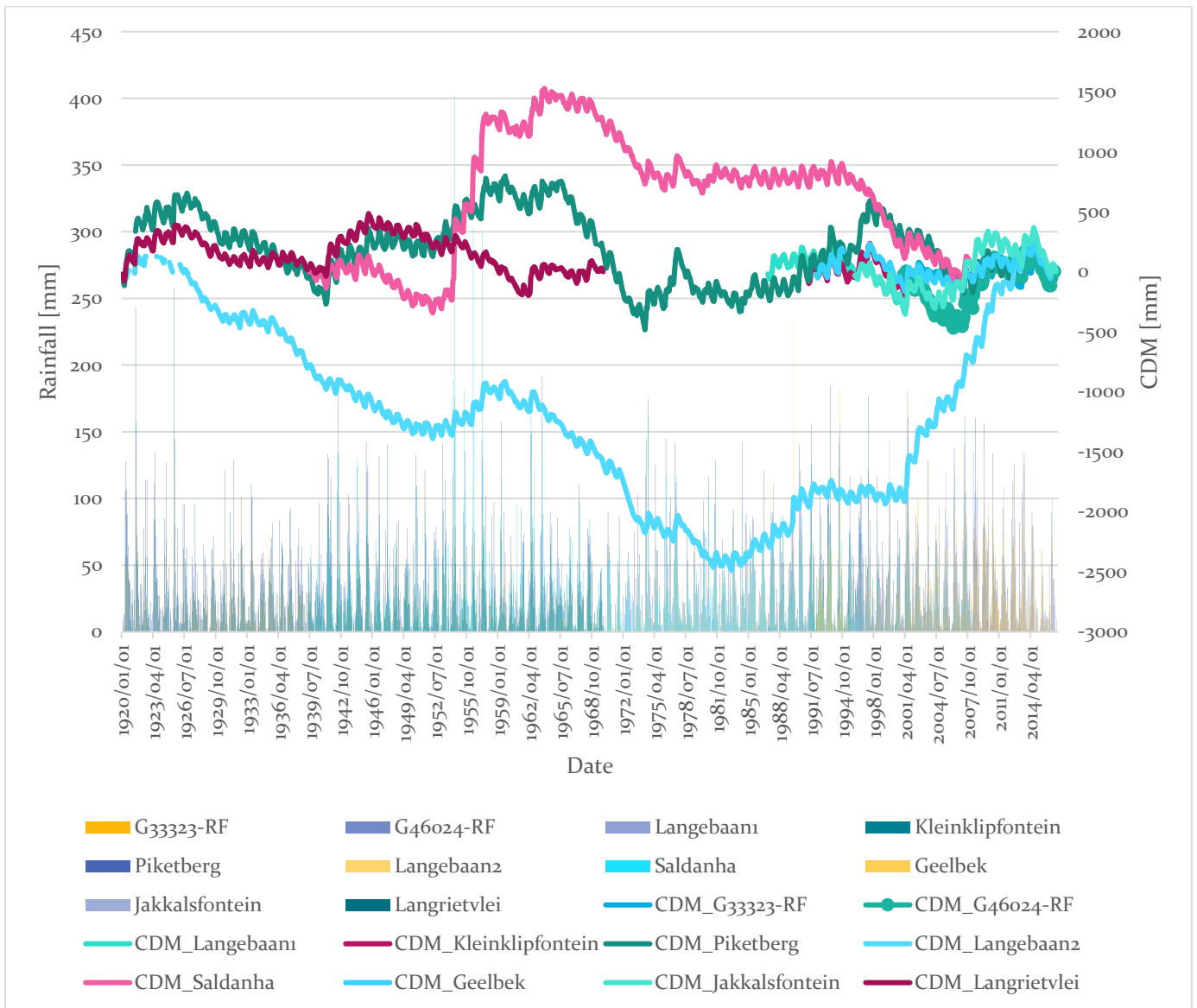


Figure 74: Time series graph of rainfall for stations in the study area.

Figure 75 shows the average rainfall for a number of rainfall stations in the study area. Most of the rainfall falls between April and September. Rain gauge G10K1 in the mountains above Aurora recorded some of the highest rainfall in the study area, with the other rainfall stations recording similar readings throughout the year.

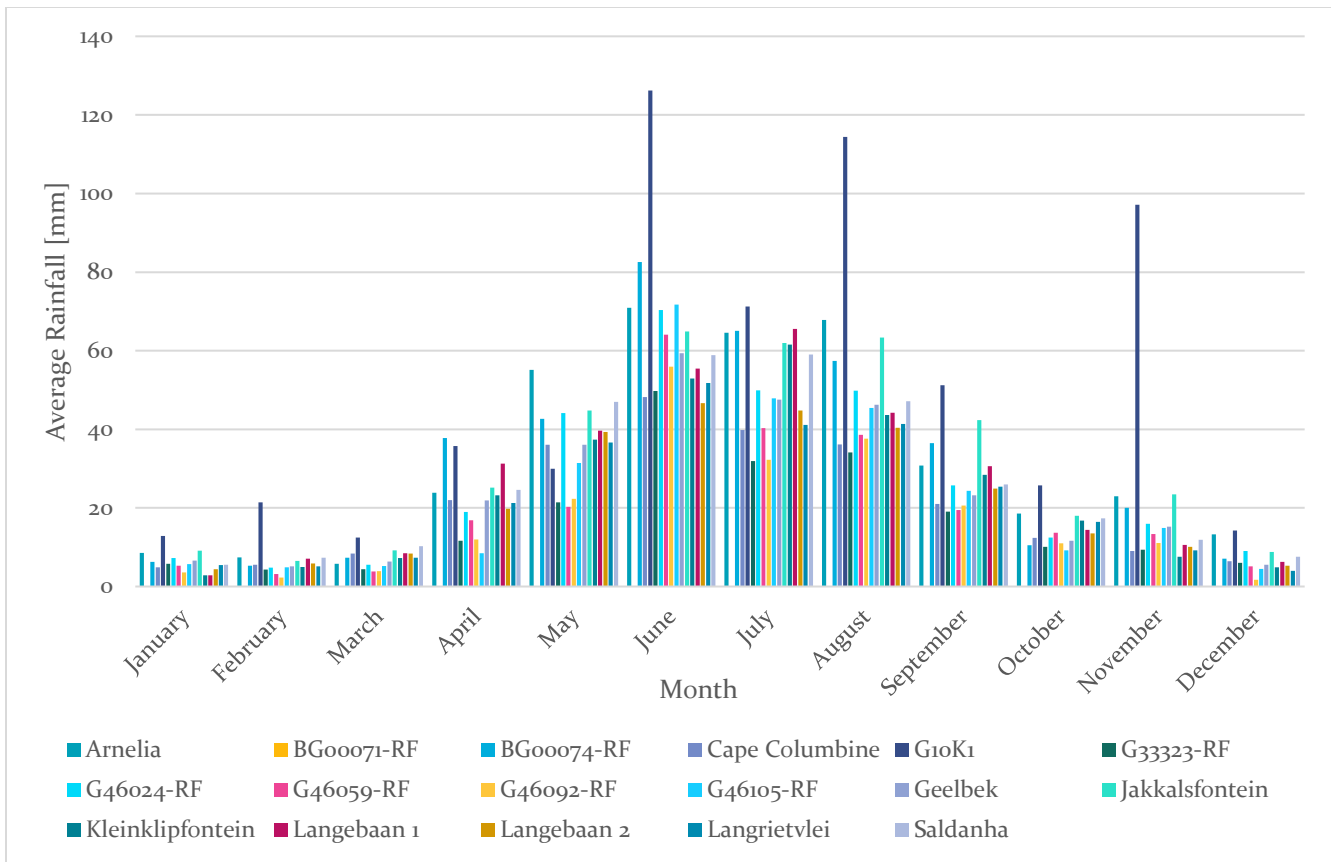


Figure 75: Average rainfall for the study area through the year.

Table 19: Summary of rainfall stations in the study area with data records available.

Rainfall station	Data Record	Years	Average annual rainfall	Maximum (year)
Arnelia	2000 - 2013	13	389.26	622 (2007)
Atlantis	1979 - 2013	34	428.06	573 (1987)
BG00071-RF	2016 - 2017	0.5		
BG00074-RF	2007 - 2016	9	368.00	510 (2014)
Cape Columbine	1936 - 2016	80	246.94	545.7 (1951)
G10K1	2010 - 2016	6	534.44	960 (2014)
G33323-RF	2001 - 2016	15	186.31	323 (2013)
G46024-RF	2001 - 2016	15	275.07	511 (2007)
G46059-RF	2004 - 2016	12	212.92	434 (2007)
G46092-RF	2004 - 2016	12	202.84	303 (2009)
G46105-RF	2007 - 2016	9	265.40	348 (2009)
Geelbek	1992 - 2014	22	278.18	384.8 (2011)
Jakkalsfontein	1996 - 2016	20	377.49	560 (2007)
Kleinklipfontein	1992 - 2001	9	290.41	442.5 (1996)
Langebaan 1	1987 - 2001	14	315.27	532.5 (2001)
Langebaan 2	1920 - 2012	92	253.57	557.8 (2001)
Langrietvlei	1893 - 2000	107	265.20	478.536 (1996)
Malmesbury 1	1993 - 2013	20	352.50	516 (1996)
Malmesbury 2	1920 - 1999	79	456.48	810 (1977)
Malmesbury 3	1999 - 2013	14	368.86	518.2 (2007)
Piketberg	1920 - 2013	93	443.42	721.8 (1996)
Porterville	1920 - 2013	93	453.16	733.6 (1977)
Saldanha	1939 - 2008	69	316.36	877.3 (1954)

The graph for the rainfall station at Langrietvlei does not give a clear 10-year cycle (Figure 76). It rather gives a 100-year cycle, which fits with the idea of multiples of 10. A 10-year moving average trendline was added to the graph to show the correlation with the CDM curve. This data record is the longest that has been found to date for a rain gauge in the study area, with continuous annual readings available from 1893 till 2000. The original data record has, unfortunately, been lost before the whole record could be captured electronically.

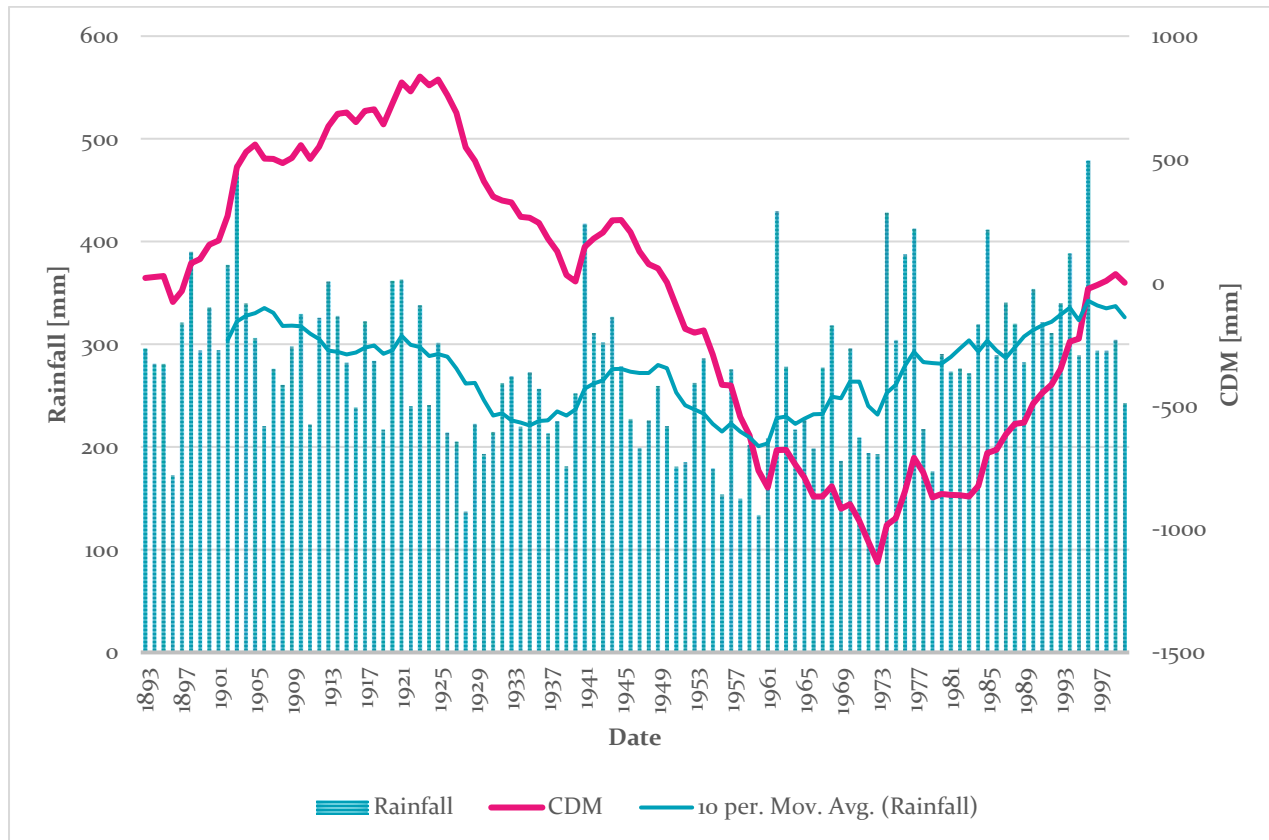


Figure 76: Time series graph for rainfall station at Farm Langrietvlei from 1897 to 2000.

4.2 Recharge

Numerous studies on groundwater recharge had been carried out around the world. This was done in a wide variety of geological settings, using different factors and parameters (Hernández-Marin et al. 2018; Coelho et al. 2017). Some consider it almost impossible to quantify recharge directly, as it is a multifaceted process that requires the inclusion of two or more concurrent estimation methods (Healy and Cook, 2002; Scanlon et al. 2002; Yin et al. 2011; Hernández-Marin et al. 2018).

Arid and semi-arid environments is considered to be the most complicated areas in which to determine groundwater recharge, as the recharge tends to be lower and more variable on a spatial and temporal scale as the aridity increases (Sibanda et al. 2009; Hernández-Marin et al. 2018). Understanding how groundwater levels respond to precipitation is important for groundwater management (Smail, et al., 2019), as it provides a measure for sustainability.

There are a number of factors that strongly affects the volume and distribution of recharge in arid and semi-arid environments. Precipitation is probably the most important, because of its scarcity. This can be coupled with high evapotranspiration rates and changes in land-use. Some studies have shown that changing the land-use from natural to agriculture had increased the recharge (Allison et al. 1990; Scanlon et al. 2007; Hernández-Marin et al. 2018).

Another factor that has an influence on the recharge to groundwater is the vadose zone. This is especially true in areas of intense groundwater pumping, where the thickening of the vadose zone causes a decrease in the recharge volume (Han et al. 2017; Hernández-Marin et al. 2018). A thick vadose zone tends to store the water instead of allowing it to percolate down to recharge the water table (Cao et al. 2016). Groundwater recharge are also affected by vegetation cover, soil type, depth to water table and the level of abstraction from a groundwater system (Ali, et al., 2012b; Emelyanova, et al., 2013).

Climate change usually impacts temperature and rainfall which affects groundwater recharge. A drier climate means that there is a reduction in rainfall and thus a decrease in recharge (Emelyanova, et al., 2013). Higher temperatures also increase evapotranspiration rates and decreases recharge.

4.2.1 Calculations

Various recharge estimations have been done in recent years. Smith (2019) used the cumulative rainfall departure (CRD) method in conjunction with stable isotope analysis. The results are, however, not available at this stage, but early work showed that local recharge only contributes a small portion of recharge to the aquifer system (Smith, 2016).

Spannenberg (2015) used the chloride mass balance (CMB) and rainfall infiltration breakthrough (RIB) methods to estimate the recharge for the unconfined layers of the Elandfontein and Langebaan Road aquifer units, as well as for the TMG aquifer above Aurora. Ebrahim (2015) used the same methods, but for the lower aquifer layers. See Table 20 for a summary of the results. Spannenberg (2015) showed the impact of the proximity to the coast on the CMB method, which makes it less reliable for use in coastal areas.

Table 20: Recent recharge estimations (¹Spannenberg, 2015; ²Ebrahim, 2015).

	Upper / Lower	CMB	RIB
Langebaan Road	Upper ¹	7.45% (G46024)	38.79% (G33323) 8.56% (BG00137)
	Lower ²	7.44% (G46023) 13.7% (BG00136)	0.12% (G46023) 5.72% (BG00136)
Elandsfontein	Upper ¹	8.61% (BG00074)	10.53% (BG00074)
	Lower ²	7.88% (G33317) 13.26% (G33505B)	0.20% (G33317) 0.69% (G33505B)
TMG		31.25% (37/1) ¹	32.84% (37/1) ¹ 18.06% (37/2) ²

The lower recharge value estimates are in most cases lower than previous values, but it is in line with the recharge estimates of Andries (2019) who used the CMB and isotopes.

4.2.2 Types of recharge observed / mechanisms

There are different types of recharge mechanisms possible in this area. This includes **direct or focused recharge** which could be from recent rainfall or irrigation return flows. Very little irrigation is taking place in the study area, with the exception of the Adamboerskraal aquifer. Most of the farmers use dryland farming methods. There is a possibility that the direct recharge may be limited as a result of the high soil water repellency, especially after dry periods. This seemed to be confirmed by recharge estimations by Smith (2016) using stable isotopes and the CRD method of recharge estimation. The possibility exist that the recharge system may be similar to that found by Nel (2009) for the Langvlei Catchment, in the Sandveld area around Elands Bay and Lamberts Bay with recharge from the Cederberg mountains through the fault systems. This would take the form of **preferential recharge** and may take place through the Colenso Fault System, sub-parallel faults, the inferred shale-granite contact, and other fractures and fissures in the bedrock. It is also possible for recharge to take place via **upward leakage** from the fractured bedrock aquifer. Recharge may also come in the form of **mountain block recharge** with the Malmesbury shale outcrops in Hopefield, the granite pluton forming the Darling hills, and the TMG mountains above Aurora and potentially also Franshhoek or Stellenbosch. **Recharge by surface water** at the Berg River flood plain is another possibility which would recharge the aquifer through lateral flow. This can be seen in the response to the 2007 flood in the Berg River with a 2- to 3-year time lag in some instances.

4.2.3 Recharge areas

The recharge areas have not been determined conclusively. Some local recharge to the Langebaan Road and Elandsfontein aquifer units most likely comes from the higher lying areas around Hopefield, and the absence of the clay layer in this area seems to increase the likelihood. The flood plain of the Berg River is another site for recharge, but it will depend on the flood levels. The delays seen in the response to the flood event of 2007 seems to fit this scenario. Andries (2019) argues that the isotope analysis shows that the Berg River is not the source of recharge to the Lower Berg River aquifer system, but the Western Cape was in a period of drought at the time that may have affected the outcome of the analysis. The aquifer would at that stage have contributed

to the river, and not the river to the aquifer system, as a result of the low water levels in the river. Smith (2016) found that local recharge seems to be small in comparison to the large volume of recharge that most probably comes from outside the study area, while Andries (2019) seems to find the exact opposite. The difference may be the result of the recharge estimation method used, and the time period of the analysis.

4.3 Water levels

Groundwater levels vary in response to the abstraction of groundwater, land use change, climate variation and climate change (Smail, et al., 2019). Spatial and temporal heterogeneity in groundwater systems limits ability of water managers to adequately derive the response of an aquifer to the different factors mentioned above (Taylor and Alley, 2001; Smail, et al., 2019). Water levels were measured as part of the DWS West Coast groundwater monitoring programme (the area between Atlantis and Dwarskersbos vs. Sandveld monitoring programme that comprises the region between Dwarskersbos and Strandfontein). Most of the water levels were measured using a dipmeter and the readings were recorded as meter below collar. There were almost 56 data loggers in the boreholes at one stage, but most of these had since been removed as a result of failure. The data loggers included Eikelkamp divers, Solinst Levelloggers, OTT Orphimedes and OTT Orpheus-Mini. The readings were taken at hourly intervals and the data analysed with Hydras 3 before being exported and captured in the DWS data base, Hydstra.

The water level readings were plotted as time series graphs. The relationship between rainfall and water levels are complex in most cases since the recharge of a specific borehole does not necessarily come from the rain that fell on site. The soil characteristics in the study site seems to suggest that only minimal recharge comes from direct infiltration. Only a selection of graphs would be discussed in this section. A complete record of the water level graphs and other information can be found in the Appendices. The results and discussion are also done by aquifer unit for ease of reference.

4.3.1 Langebaan Road aquifer unit

Figure 77 gives an overview of the distribution of monitoring points on the Langebaan Road aquifer unit. The red polygon shows the location of the wellfield.

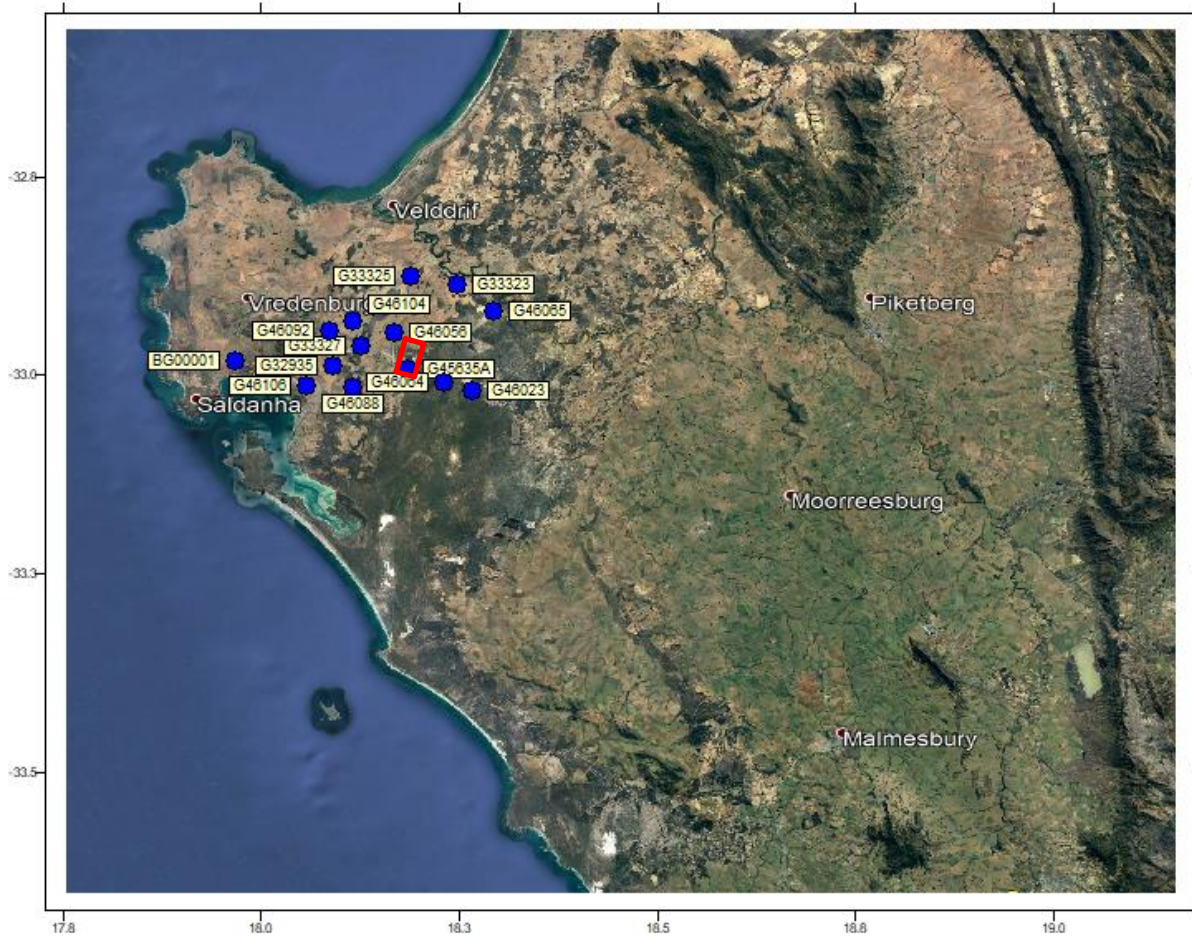


Figure 77: Satellite image showing the distribution of a selection monitoring points for the Langebaan Road aquifer unit (WISH; Lukas, 2012).

Borehole G33323 was drilled in 1984 and is located close to the Berg River. It is in the confined aquifer layer of the Langebaan Road aquifer unit and seems to react fairly quickly to rainfall events (Figure 78). This makes the patterns overserved in the water levels difficult to explain, as the pattern would usually be associated with a borehole in an unconfined aquifer that responds directly to recharge. It is possible that there is leakage along the casing or that the casing has been breached, connecting the borehole to the upper aquifer layer. It is also possible that it is linked to flow in the Berg River. There is a clear seasonal trend in the water levels, with the highest water levels usually measured between August and November. The water levels have a downward trend from 2001 to 2007, when flooding in the Berg River may have recharged the aquifer. The peak of this rise was measured in October of 2007, where after the water levels began declining until May 2012. Good rains fell again late in 2013 and in 2014, after the low rainfall of 2011 and 2012. This led to a peak in water levels in August 2014. The recent drought began in 2015 and can be seen in the declining water levels since August 2014. The increase in rainfall in early 2019 should lead to an increase in the water levels in this part of the aquifer.

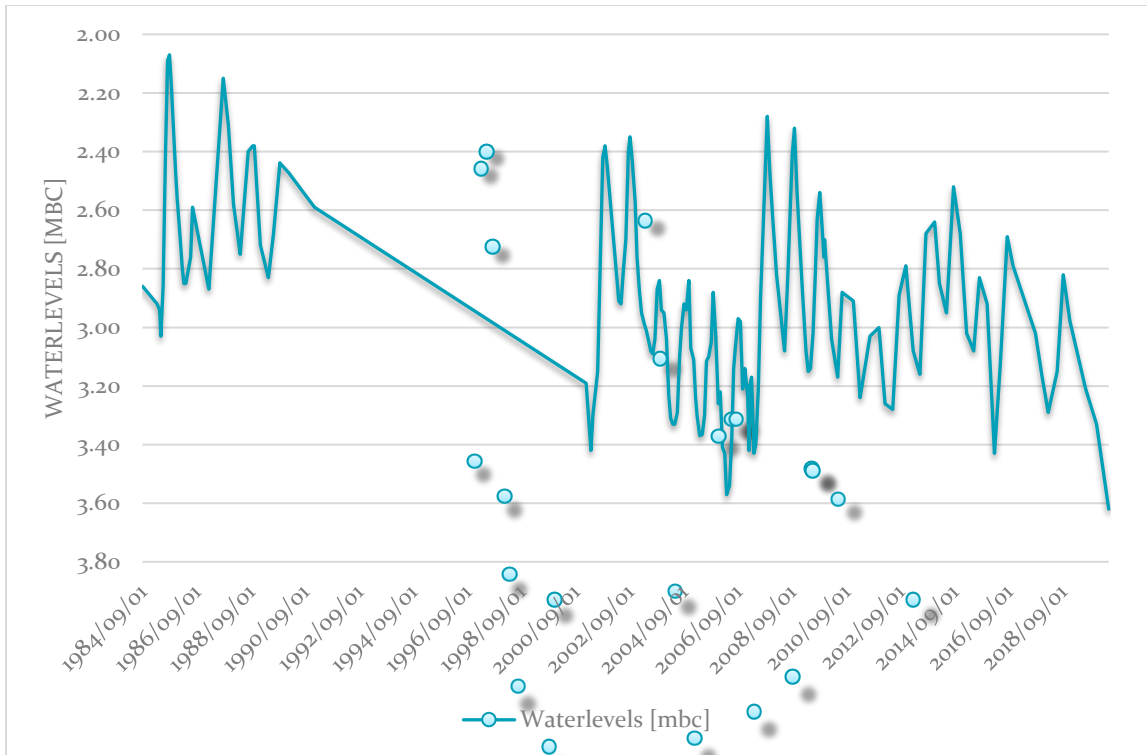


Figure 78: Time series graph of water levels for G33323.

An attempt has been made to recreate the graphs used in the management of dams for groundwater levels. Dams usually have a specific storage volume, and it is thus easier to determine the percentiles against which to measure current dam levels, even though historical trends in dam levels also play a role. Plotting the same graphs for groundwater levels is more complex and the historical background changes with time. It was not possible to use the complete historical record for this analysis, because of the almost 10-year monitoring gap. The analysis was thus started when monitoring resumed between 1998 and 2001. The graph uses hydrological years stretching from the beginning of October of one year to the end of September the following year. Figure 79 shows the resulting plot for G33323. The curves for 2007 and 2013 is the highest, lying mostly within the 90th and 95th percentile. The years with the lowest curves are from 2015 to 2017, with some of the curves falling below the historical record for part of the hydrological year.

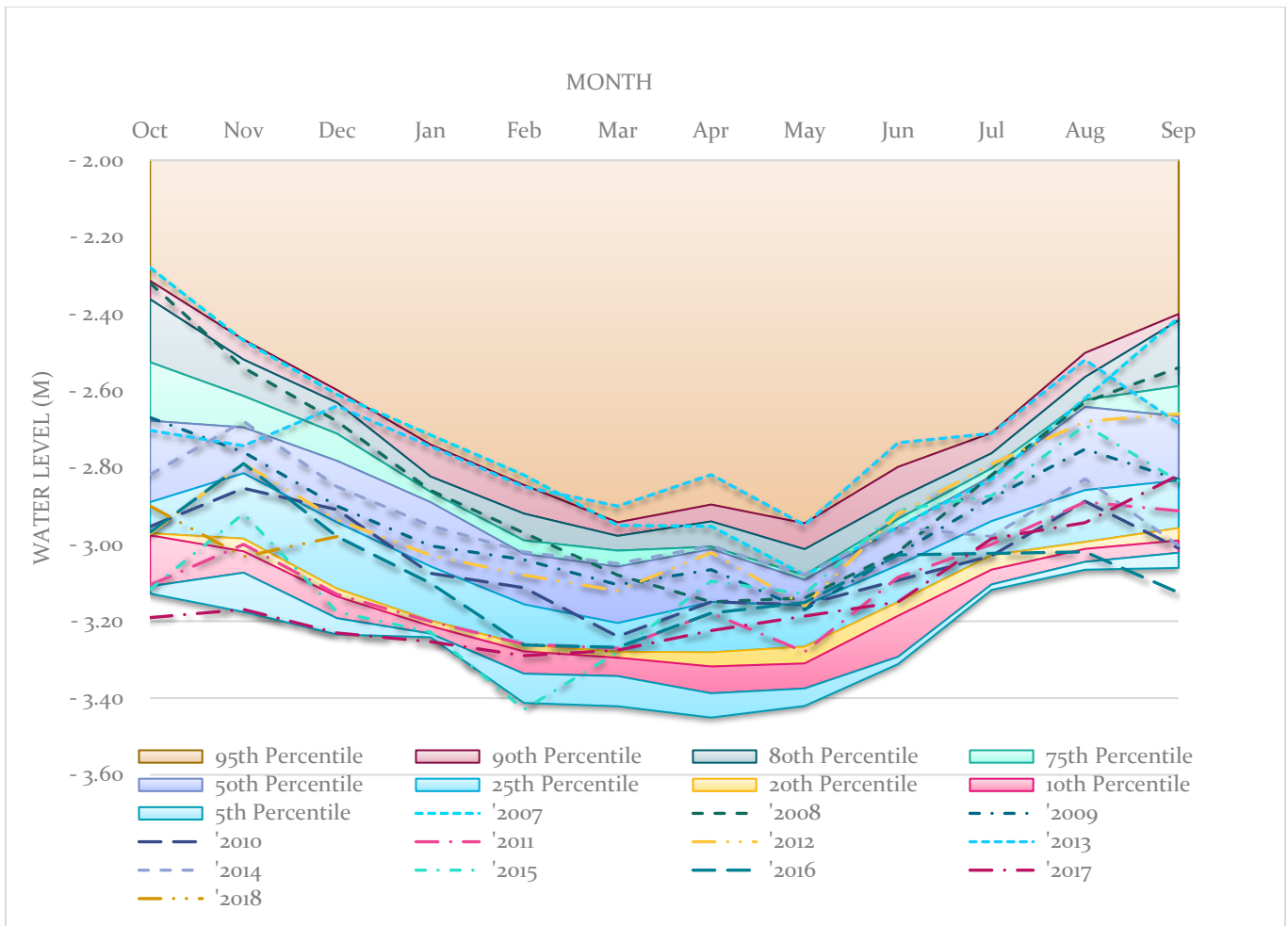


Figure 79: Graph showing the variation in water levels in a hydrological year for borehole G33323 on the historical background.

Harter and Brewster (2018) used the groundwater level change index method to determine whether groundwater levels in California recovered with the first good rainfall year after their recent drought. A groundwater level change index for an area is determined by subtracting the percentage of boreholes with increasing water levels from the percentage of boreholes in the state with decreasing water levels over a specific period of time. A positive value provides an indication that more boreholes had increased in water levels, while a negative value show that more boreholes had lower water levels. The index was determined for 1-, 3-, 5- and 10-year periods preceding each year from 2012 to 2017. The long-term trends for the first three indices are similar to the precipitation trends, where an increase in the precipitation deficit correlates with the groundwater level change index becoming more negative. The 10-year groundwater level change index does not correlate as closely with the precipitation trends. This analysis only includes the first step in the method.

The first step of the method is to calculate the groundwater level change index for individual boreholes. This is done by calculating the difference in consecutive water level values using one reading per year, usually the one measured in September as it the end of the hydrological year. The water levels in the study area would be close to the highest for the year in September, as it is

at/near the end of the wet season in the Western Cape winter rainfall area. This would, however, depend on the time it would take for the aquifer to respond to rainfall/recharge events.

The older value is then subtracted from the newer value and tabulated. The change index is then calculated at a 1-, 3-, 5- and 10-year intervals (Harter and Brewster, 2018). This provides a way to compare the changes in water levels between different boreholes at different elevations and in different aquifer layers, without having to convert the water level to mamsl or some other common reference point. A graph is then plotted with the annual water level and the groundwater level change index for the different time intervals. water level Figure 80 shows the graph for borehole G33323. The water levels had remained fairly steady since 2001 with a fluctuation of less than a meter for this period.

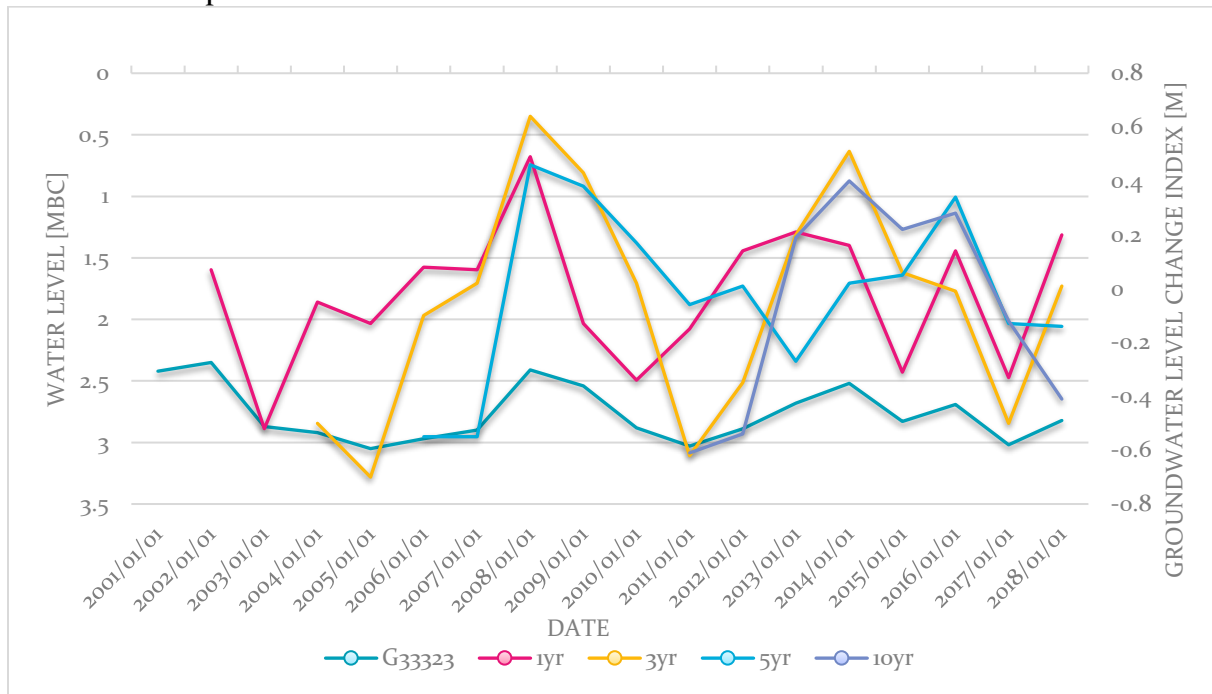


Figure 80: Groundwater level change index of 1-, 3-, 5- and 10-year intervals for G33323 with annual water levels.

Borehole G33327 was also drilled in 1984. It is in the lower semi-confined to confined layer of the Langebaan Road aquifer unit. It is about 12km from the wellfield near the old phosphate mine, now the West Coast Fossil Park. It is responding to the abstraction at the wellfield, with an almost immediate response (see Figure 81). The wellfield became operational in December 1999, which can be seen in the steep drop in water levels. There was concern that the abstraction was having a permanent detrimental impact on the aquifer, and it was decided to test this in 2004 by resting the wellfield for 3 months while the pumps were serviced/repared. This can be seen in the recovery of water levels. Based on the recommendation of the monitoring committee there was a voluntary 10% reduction in the volume abstracted from what was allowed on the water use licence.

The water levels dropped again after abstraction resumed in 2004. The next two peaks are the result of the artificial recharge / managed aquifer recharge test that was done in 2008 and 2009 by the CSIR for DWS (then DWAF). These peaks follow a smaller peak that was the result of the

natural recharge to the system due to the flooding in the Berg River flood plain in 2007. The years 2007 to 2009 were all good rainfall years and it masked the effectiveness of the MAR test. The water levels dropped after the MAR test was completed and it reflects the poor rainfall of 2011 and 2012. It is interesting to note that this decline in water levels is not as steep as the decline in 1999 onwards when the wellfield become operational. The response to the higher rainfall in 2013 and 2014 were combined with the results of vandalism at the wellfield. The electrical wires were dug up and stripped on site in late March/early April of 2013, and shortly afterwards the pump houses were vandalized. This resulted in the wellfield not being used for a number of years and can be seen in the recovery of the water levels. The repairs were completed in 2015 or 2016, but further security measures were needed after renewed vandalism (Faasen, 2016). The wellfield became operational again near the end of 2017, with the lowest level in 2018 (June 2018 with the water level reading at 17.56mbc) at the height of the Western Cape drought and Saldanha only days away from running out of water (Maj, 2020). The reading taken in June 2018 was the lowest recorded reading for this borehole.

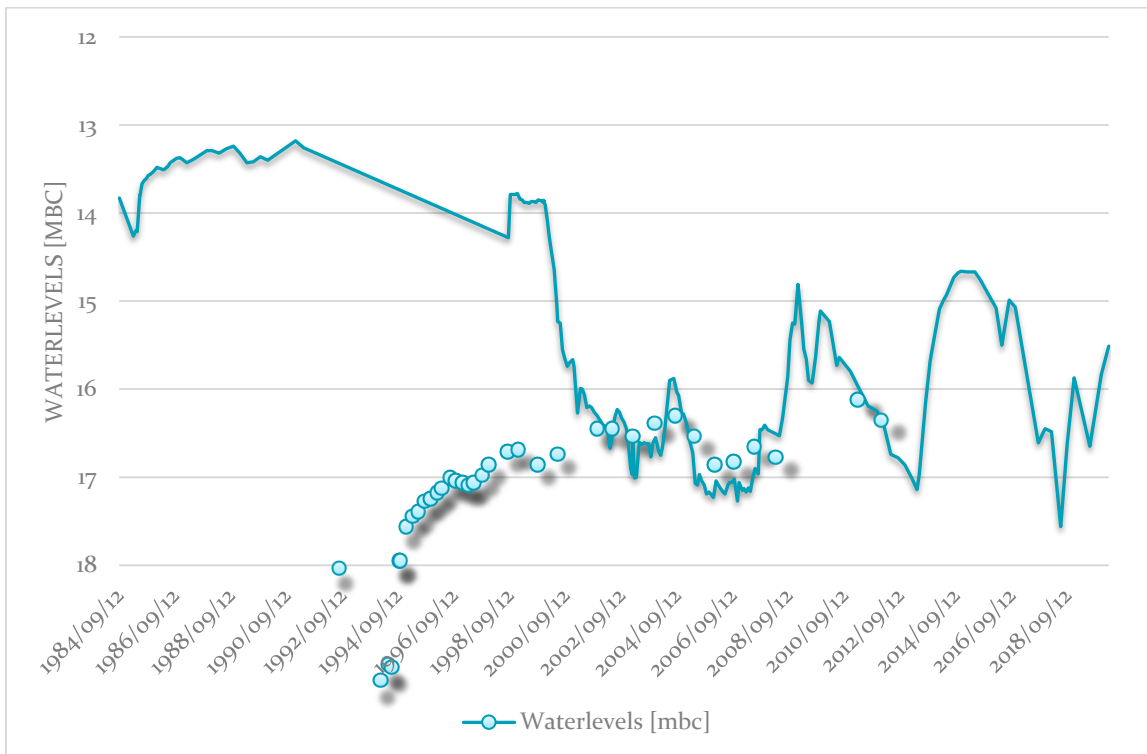


Figure 81: Time series graph of water levels for borehole G33327.

Figure 82 shows the water level measurements for G33327 compared to the abstraction volumes at the Langebaan Road wellfield. There is a clear correlation of the water levels in the boreholes with the abstraction volumes. Unfortunately, very little abstraction data was available after July 2009. The higher abstraction during the drought can be seen in the data for 2017 (WCDM, 2018) and 2018 (WCDM, 2019). The grey part of the bar chart was the volumes injected into borehole BG00136 as part of the MAR test. A comparison of the water levels for G33327 will be done below when the correlation of water levels and rainfall is discussed.

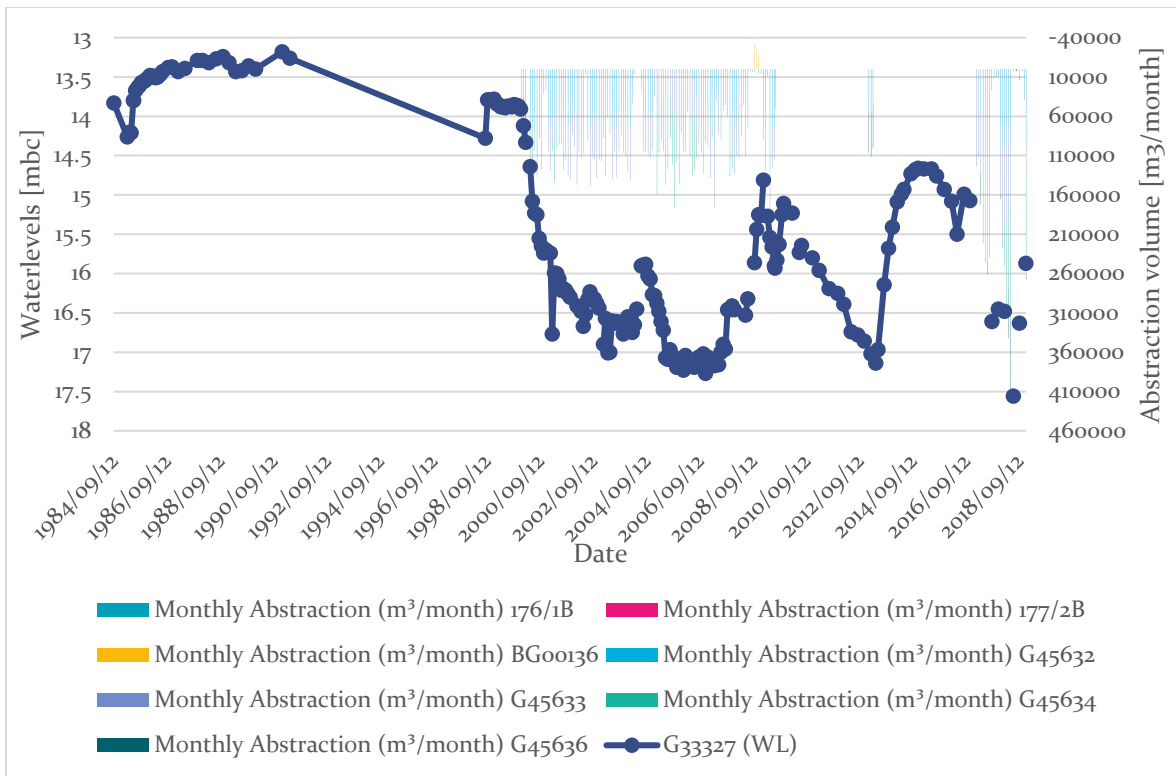


Figure 82: Time series graph showing the water levels measured in borehole G33327 compared to the abstraction at the Langebaan Road wellfield.

The water levels in the borehole against the historical background (Figure 83) did not respond to the 2007 natural recharge event, possibly as a result of the abstraction that was taking place. Even the response to the 2008 and 2009 MAR test was not immediate. There is, however, a cumulative response that can be seen in this case and others that are impacted by the abstraction. Other boreholes in the semi-confined to confined aquifer layer that measures background values also show a delayed response to the recharge event of 2007 with the water levels reaching their highest levels only in the 2009-10 hydrological year. The lower rainfall of the 2010-11 and 2011-12 hydrological year is clearly visible in the lower level of the curves. The recovery in the 2013-14 year as a result of the higher rainfall and the recovery after the vandalism reaches its highest levels in the 2014-15 hydrological year. The drought that began in 2015 can be seen in the declining levels of the next curves and the graph dips below the historical record in the 2017-18 hydrological year as a result of the higher abstraction volumes to prevent the Saldanha Bay Local Municipality from running out of water. The incomplete 2018-19 cycle shows recovery.

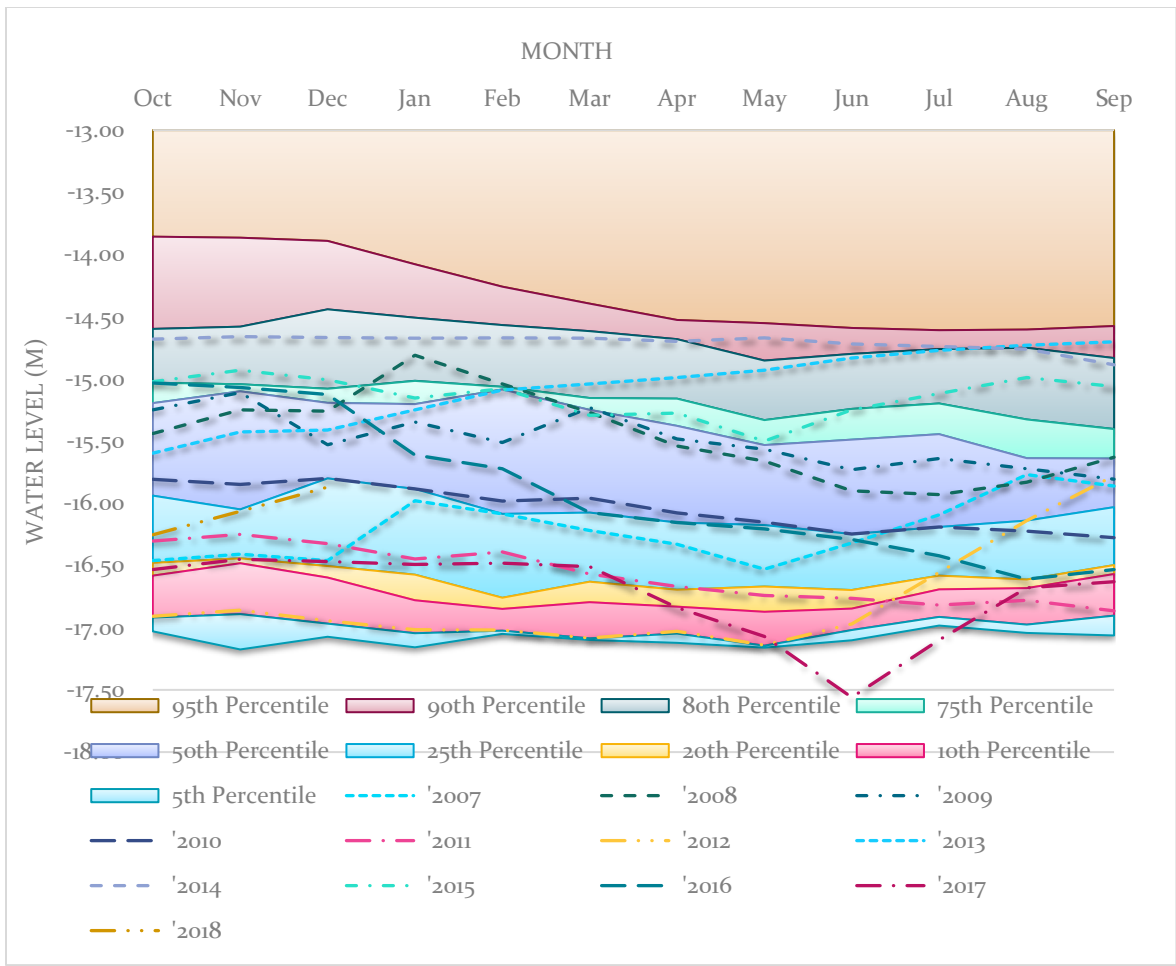


Figure 83: Graph showing the variation in water levels in a hydrological year for borehole G33327 on the historical background.

The water levels in the groundwater level change index (Figure 84) shows the water level history of G33327 in summary, with the 2004, 2008-2009 and the effects of the 2013 vandalism seen as peaks in the curve. The indexes of the different time intervals tend to mimic this trend as well.

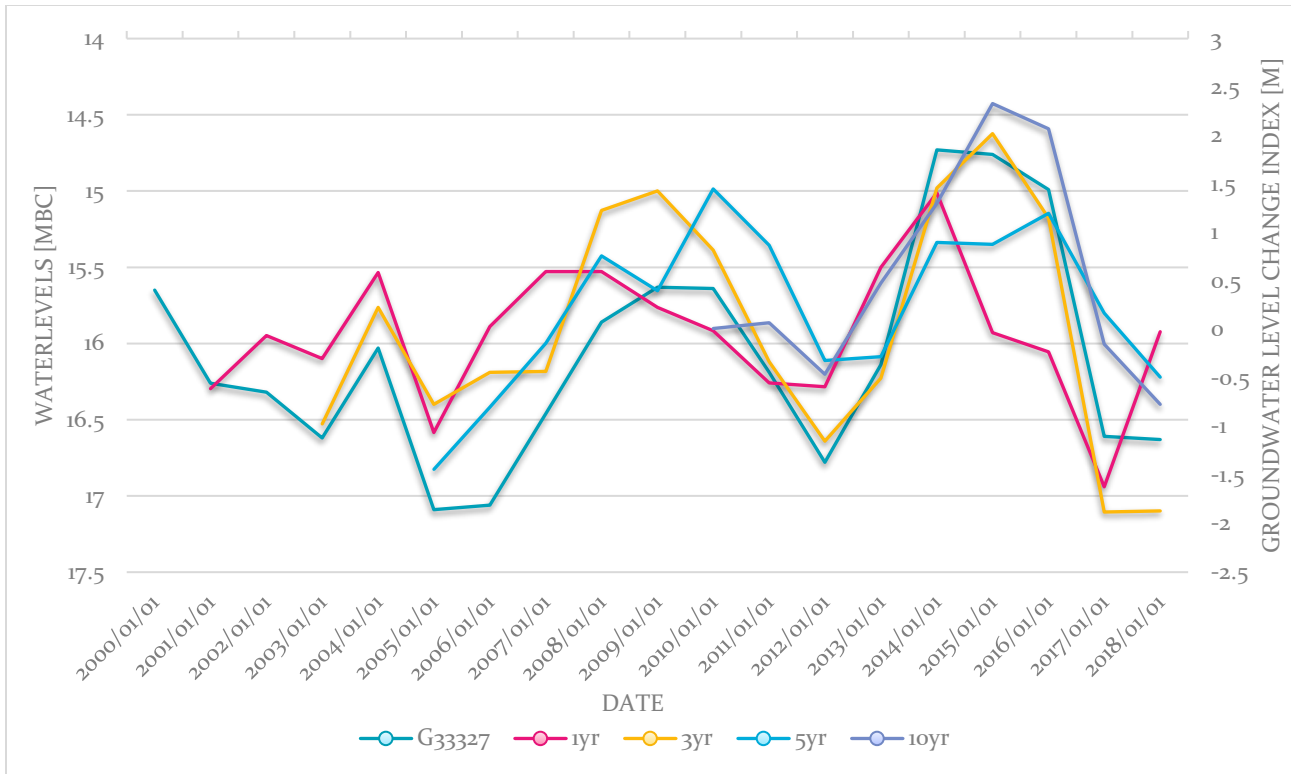


Figure 84: Groundwater level change index for borehole G33327 – 1-year, 3-year, 5-year and 10-year intervals.

Figure 85 shows a comparison between water levels of the upper and lower aquifer layer at the Langebaan Road wellfield. G45634A was plotted on the secondary x-axis, while the other two data records were plotted against the primary x-axes. This was done in order to compare the patterns in the data records. G45634A is a lower aquifer layer borehole and G45634B is an upper aquifer layer borehole. They are monitoring boreholes next to production borehole G45634. G46032 is an upper aquifer layer borehole downgradient of the wellfield. It is clear from the graph that there is no correlation between the water levels of the upper aquifer layer and the lower aquifer layer. G45634A clearly shows the impact of the abstraction, artificial recharge and vandalism on the water levels in the borehole. G45634B shows a seasonal variation that fluctuates between 2 and 3mbc. The water level readings for G46032 varies between 3 to 5mbc, with distinct recharge events in 2001 and 2007. This correlates well with the rainfall patterns in the area.

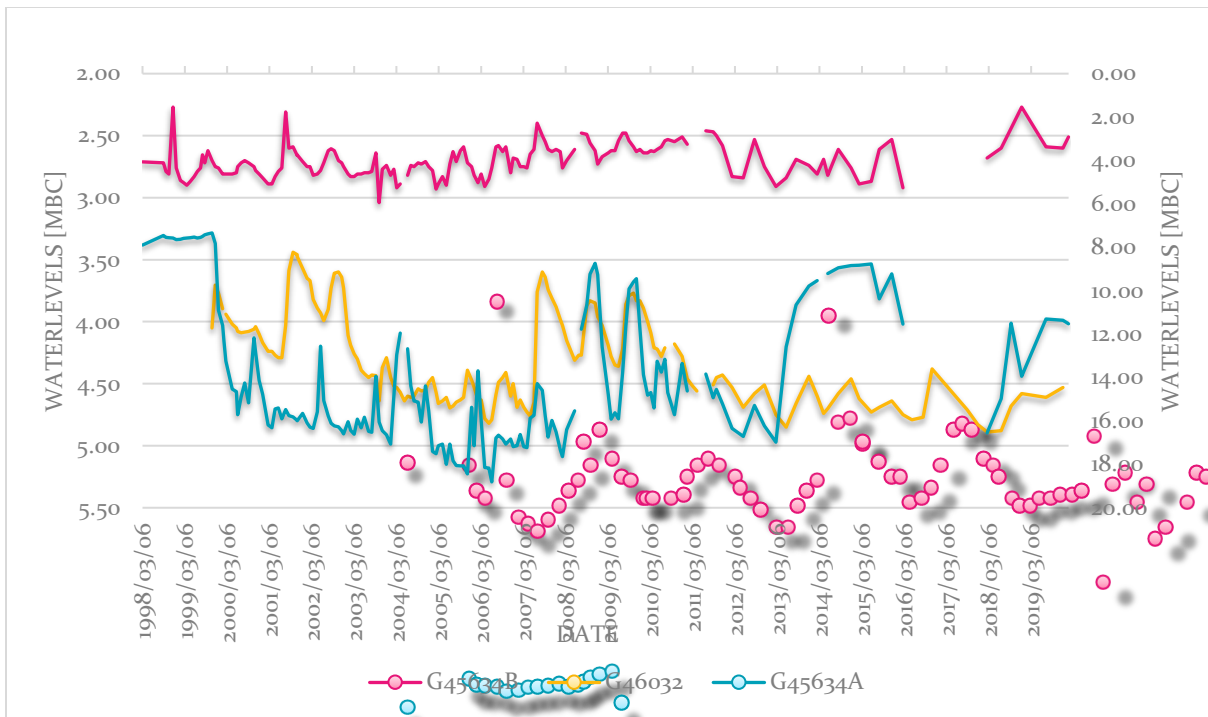


Figure 85: Time series graph comparing waterlevels from the upper and lower aquifer layers at Langebaan Road wellfield.

Correlation between water levels and rainfall

Figure 86 shows the water levels of G33327 with the rainfall of five of the DWS rain gauges in the area. G46024-RF (between boreholes G46023 and G46024) was the first one put up by DWS in this area and has the longest data record. G33323-RF is next to borehole G33323 and was the second rain gauge to be installed. The other three is located next to the borehole with the same name and has shorter data records. Gaps exist in this record for the times when the Thalimedes failed, but the combined data record gives a fairly complete picture of precipitation in the area. The rainfall measurements of the five rain gauges do differ as to the volume measured, since they are located in different areas of the study site.

The graph shows very little correlation between the water levels of G33327 and the rainfall measurements. The effects of abstraction have a far greater influence on the water levels at this lower aquifer layer borehole (Figure 82) than the rainfall. Direct recharge can thus be ruled out for the lower aquifer layer.

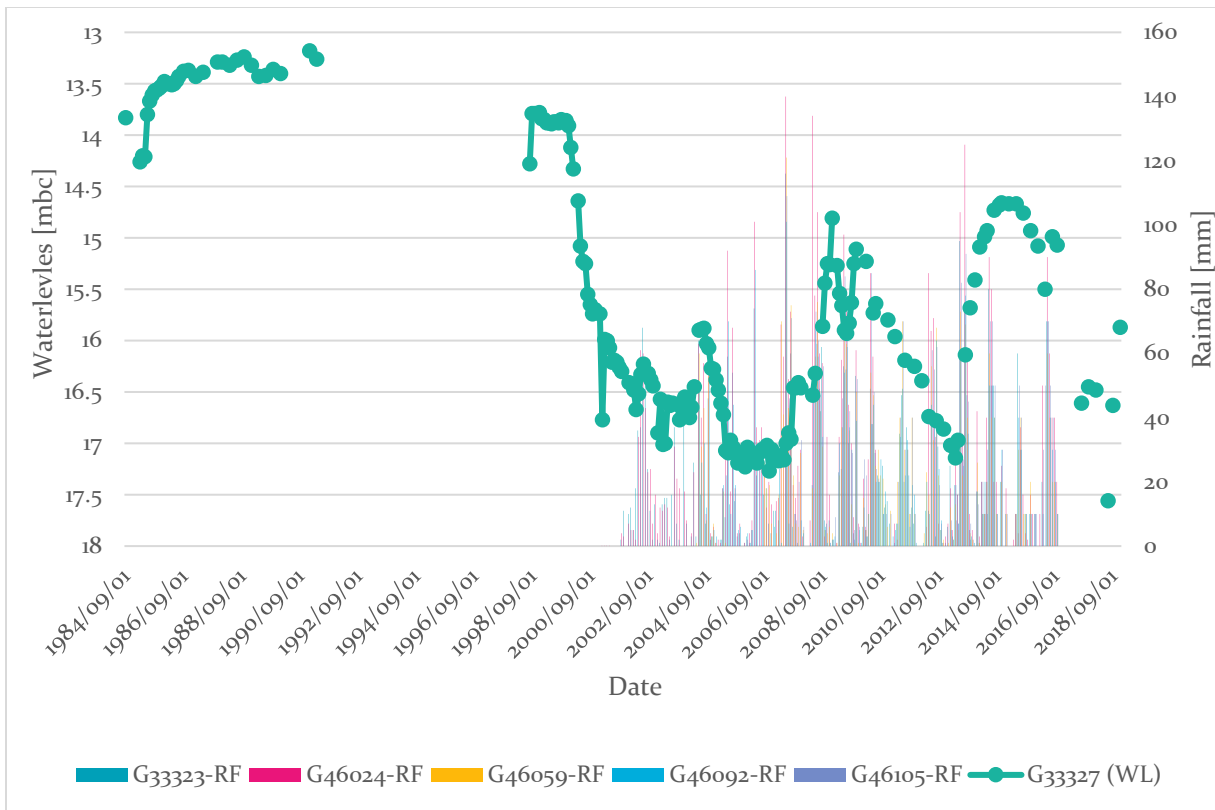


Figure 86: Time series graph showing the water levels as measured in borehole G33327 compared to the rainfall measured in the DWS rain gauges in the area.

There is a higher correlation between rainfall (blue line, cumulative for each hydrological year) and water levels at borehole G33323 and the rain gauge G33323-RF (Figure 87) than with G33327. The graph was generated using the OTT Hydromet programme Hydras3. The water levels seem to respond quickly to recharge events and the peak in the water levels often coincide with the end of the hydrological year. The black line indicates the logger data for the borehole, which is equipped with an OTT Orphimedes. The red line represents the hand readings. The interval of measuring hand readings varied between monthly and quarterly and at times even less frequently. This would explain some of the deviations from the logger curve. Loggers also tend to drift at times, with the drift being more prominent in some loggers. Direct recharge for upper aquifer layers is thus a possibility, but recharge can potentially also take place from the Berg River.

† G33323/Cloetes kraal/Waterlevels@G33323
 * G33323/Cloetes kraal/Waterlevels@G33323
 ▲ G33323_RF-/Rainfall@G33323_RF1

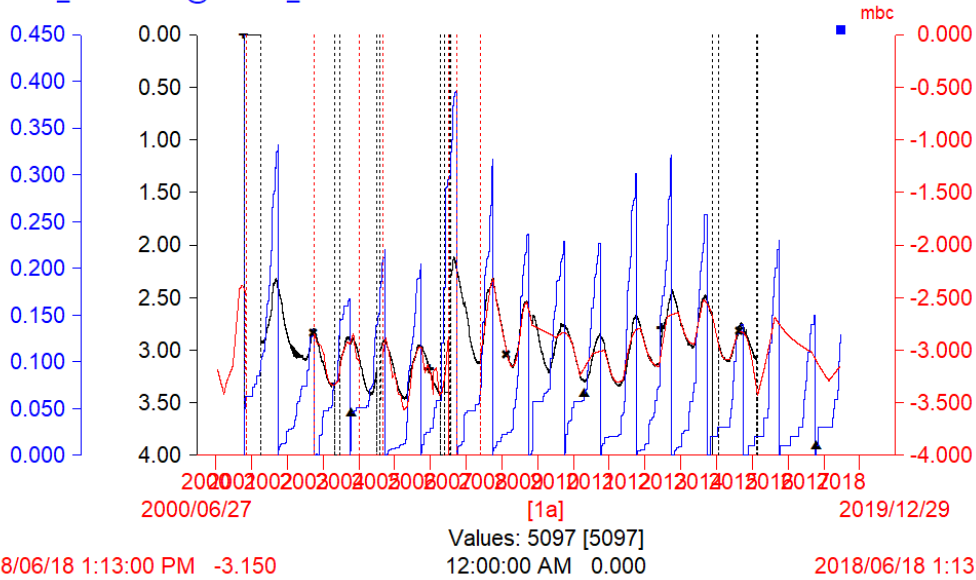


Figure 87: Graph showing the correlation between water levels and rainfall for G33323 and G33323-RF.

Figure 88 shows the same data as in Figure 87, but the rainfall is recorded in monthly readings. There is a fairly good correlation between the highest rainfall events and the p. The six-month moving average curve is similar to that of the water level curve but seems to be the inverse of the pattern observed in the water levels.

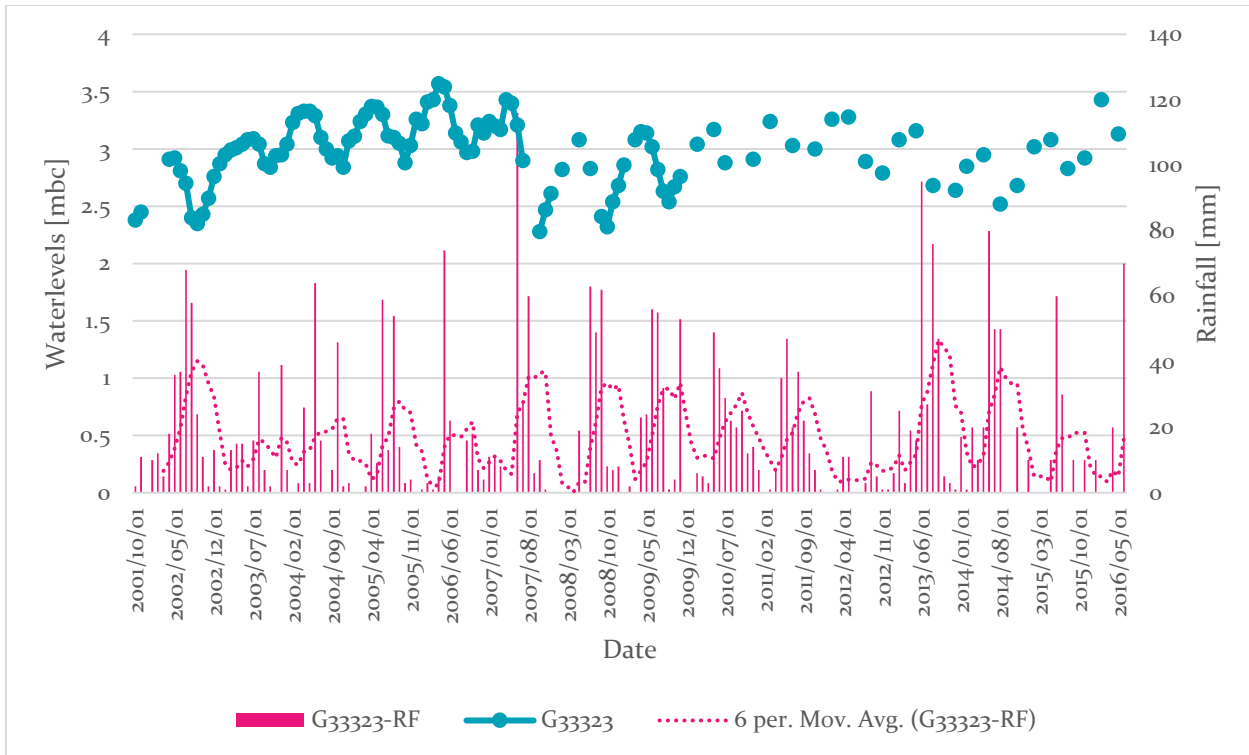


Figure 88: Water levels in borehole G33323 compared to the rainfall measurements in G33323-RF, with a 6-month moving average.

Figure 89 shows the CDM values for the rainfall measured at G33323-RF, compared to the water levels. There is a clear correlation between the cyclical pattern of the two curves, but the curves do not fit close together for most of the data record. The period between 2007 and 2009 shows the closest fit between the two curves.

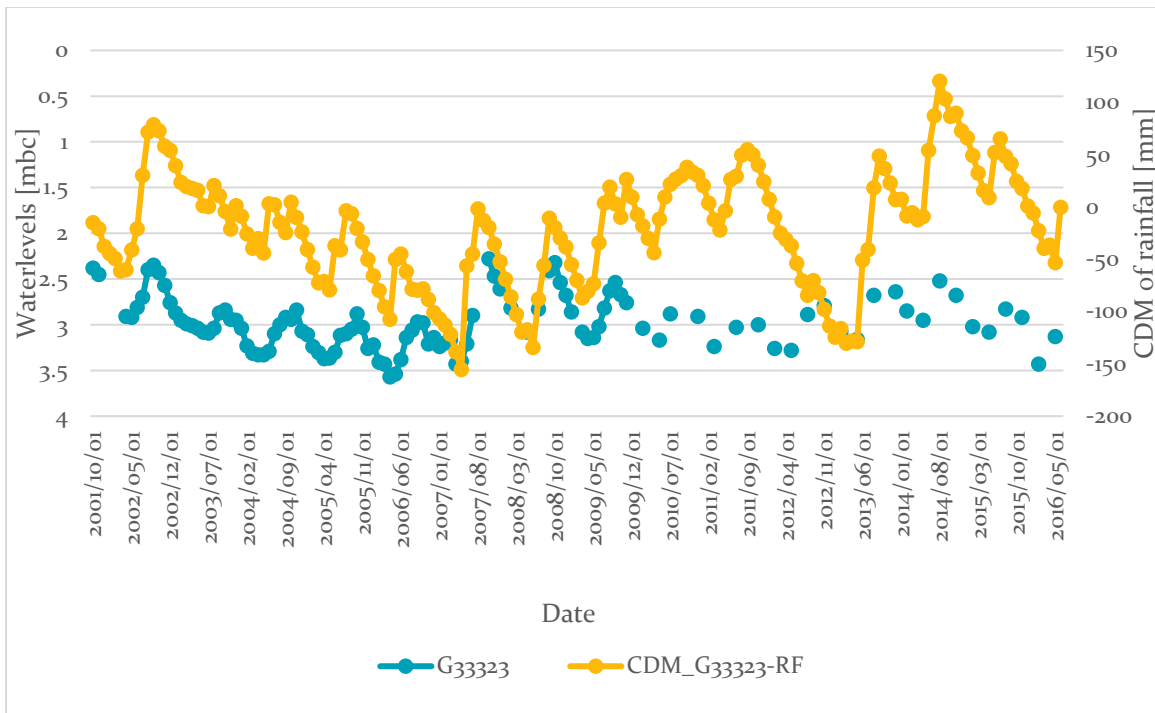


Figure 89: Water levels in G33323 compared to the CDM of the rainfall readings of G33323-RF.

The boreholes G46023 and G46024 are monitoring boreholes that were drilled shortly after the development of the Langebaan Road wellfield with the purpose of monitoring the impacts of the abstraction. The boreholes are about 8km from the wellfield along the R27 that runs between Vredenburg and Hopefield. The understanding is that local recharge comes from this area towards Hopefield (Tredoux and Engelbrecht, 2009; Tredoux and Talma, 2009). The conceptual model developed by Tredoux and Engelbrecht indicates a clay layer between the two boreholes, but this could not be confirmed with borehole logs as the records are apparently lost. There are, however, different sedimentary deposits in the area, as the water levels indicate. The scales of the water levels were adjusted to be able to fit the two curves as closely as possible (Figure 90). It is clear that the two data sets follow the same pattern and are closely linked with the rainfall pattern. It would thus seem that if a clay layer is present, the effect of it is negligible. The basement contour map by Smith (1982) indicated a second palaeochannel flowing into the main palaeochannel for the Berg River. It is possible that these boreholes are on the side channel, which could have been the palaeochannel for the Sout River. This could explain the apparent absence of the clay layer. Recent drilling of the Hopefield 2 wellfield in this area has confirmed that there is no clay layer in the area adjacent to these boreholes (Nel, 2019). It is possible that local recharge to the lower aquifer layer could take place through areas like these where the clay layer is absent.

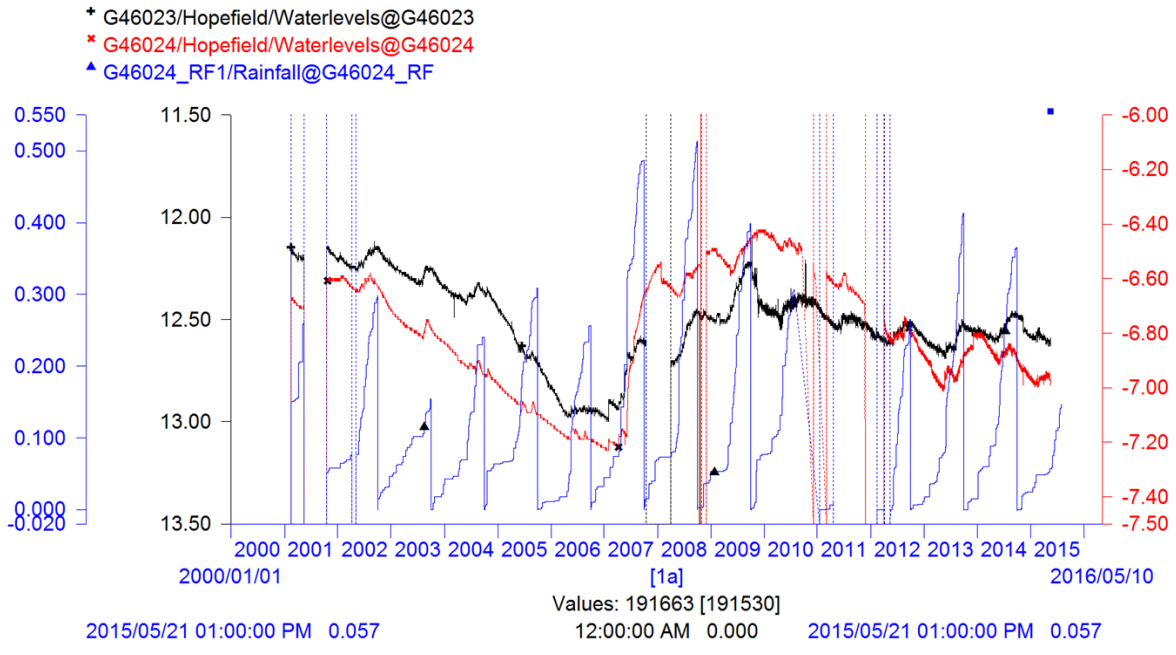


Figure 90: Graph showing the water levels for boreholes G46023 and G46024 with the rainfall recorded by G46024-RF (Hydras3).

4.3.2 Elandsfontein Aquifer Unit

The Elandsfontein aquifer unit has similar layers as that of the Langebaan Road aquifer unit, with the difference that the layers tend to be thicker. There is also stronger dune formation in this area of the Lower Berg River. Figure 91 shows the distribution of monitoring points on the Elandsfontein aquifer unit.

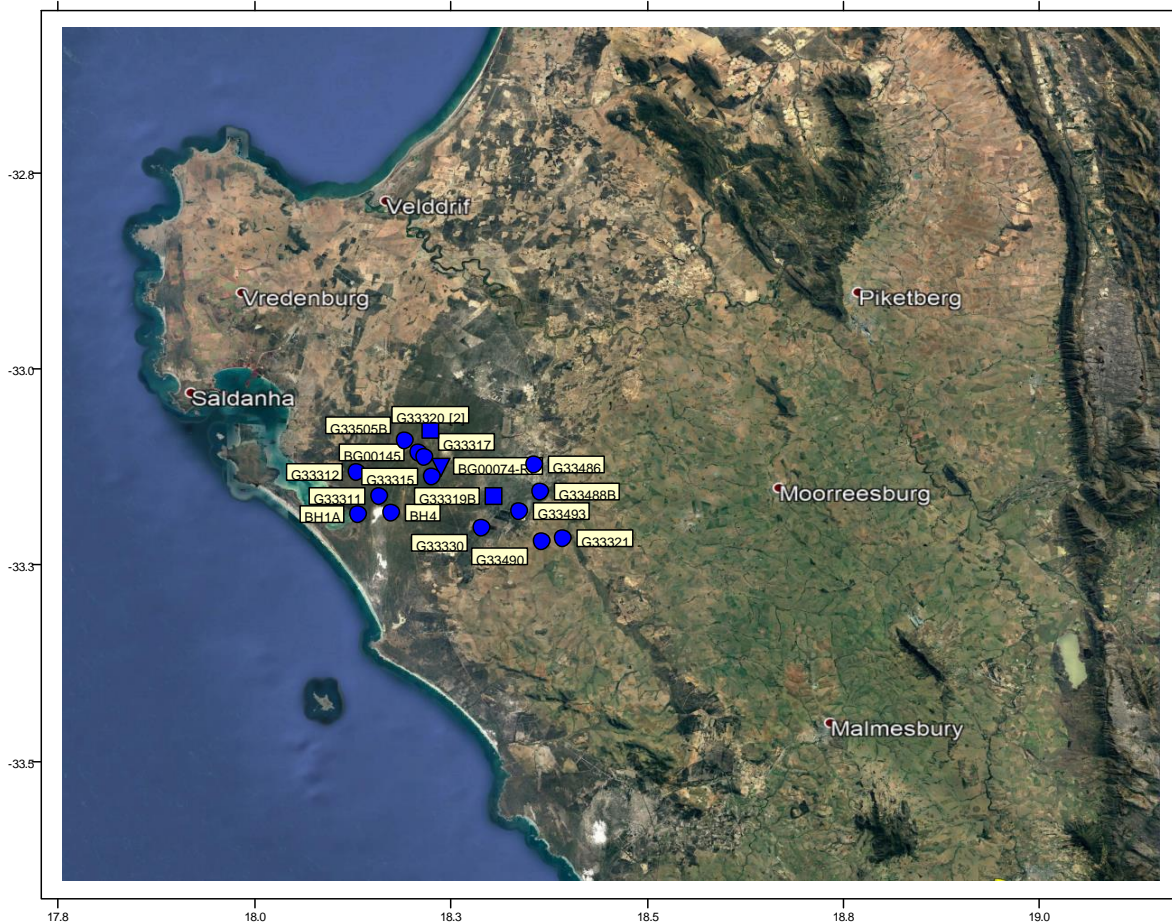


Figure 91: Satellite image showing the distribution of a selection of monitoring points on the Elandsfontein aquifer unit (WISH; Lukas, 2012).

Borehole G33329 (drilled in 1984) is located at the lower end of the Elandsfontein aquifer unit and is equipped with 4 piezometers at different depths (Figure 92). This borehole, together with G33314 was set up as the observation boreholes for the test borehole G33330. G33330 has screens in both the upper and lower aquifer layer and pumping tests was done via Packer tests. The tests did not prove to be very successful, with Timmerman (1985b) citing faulty construction as one of the reasons. It is the only site on the Elandsfontein aquifer unit where pumping tests were carried out during the early investigations. Figure 93 shows the graphs for the four piezometers. The water levels were not adjusted for the difference in height between the different piezometers. Piezometer 1 is the deepest of the four, with water levels between 15 and 22mbc. The water levels of piezometer 2 varied between 7 and 12mbc. Piezometers 3 and 4 were always close together, with water levels fluctuating between 5 and 7mbc. Piezometer 3 are usually the deeper one of the last two piezometers.

It is difficult to correlate the water levels before 1991 to those after 2001 when monitoring was resumed. The original notes that went with the early monitoring data were not preserved and no record exists of what happened in the gap period. This can be seen in all the boreholes that was

drilled before 1998. Water levels in all four piezometers show a steady decline since 2000, with is about a year after the Langebaan Road wellfield become operational. There was no other impact in the area. The only possibility other than natural impacts would have been the fact that the abstraction at the wellfield was impacting water levels in the Elandsfontein aquifer unit. The decline in water levels may be small, so as not to look very significant. Small variations are, however, very important in confined and semi-confined systems. What is interesting is that all the water levels seemed to respond the same at the time. There is a levelling out of the decline over time, and it would seem that piezometers 3 and 4 began showing more natural responses to the rainfall events. This can be seen in the higher water levels around 2009, which is at the end of the 2007-2009 wet cycle. It again peaks in late 2014 coinciding with the 2013-2014 wet cycle.

The farmer abstracted water from G33330 around April 2005, with the largest impact in the water levels of piezometer 3, which is presumably the depth of the first screen of G33330, and the layer on which this piezometer is situated. Piezometers 1 and 2 also showed a response to the abstraction, with piezometer 2 showing no recovery in water levels. The water levels of piezometers 1 and 3 did recover. The water levels of piezometer 4 were not impacted by the abstraction, which indicates that piezometers 3 and 4 are in different layers that are hydrologically separate from each other.

No explanation can yet be given for the variation in water levels for piezometer 2 in the 2009-2011 period, but it would seem that the rise in 2015 may be a delayed response to the better rainfall for the 2013-2014 period. No explanation can be given for the fluctuations in water levels for 2011 and 2014 for piezometer 1 either.



Figure 92: Photograph showing the four piezometers of G33329 (taken on 21 January 2009).

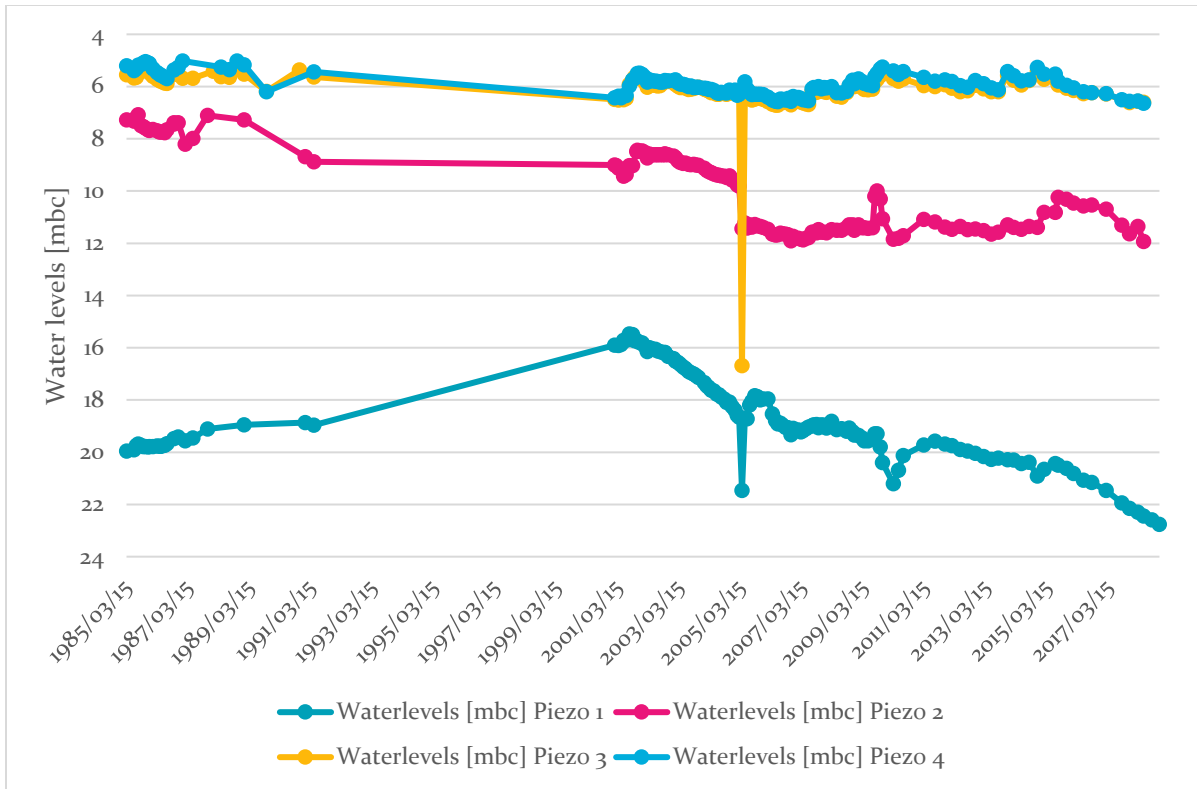


Figure 93: Time series graphs for the four piezometers of G33329.

G33317 was drilled in 1984 and is located in close proximity where the stratigraphic type borehole for the Elandsfontyn Formation (G30878) was drilled. It has screens in the upper and lower aquifer layers and was designated as a monitoring borehole. The screens in both aquifer layers can act as a link between the two aquifer layers, but this should not have made a big difference under natural conditions. The hydrostatic pressure of the lower aquifer layer and the downward pressure of of the upper aquifer layer would have kept the system in dynamic equilibrium. Disturbances to the system, such as large-scale abstraction would, however, disrupt this equilibrium.

According to the bedrock contour map of Smith (1982), this borehole is located in the middle of the palaeochannel, where it changes direction. Figure 94 shows the changes in water levels for borehole G33317. The water levels were stable with very little fluctuation before 1991. It has a fairly steep drop from September 2001 (13.13mbc) for the next five years, most probably as a result of the abstractions as the Langebaan Road wellfield whereafter the water level decline is less steep. In November 2016 it reaches a level of 15.17mbc, which is only an approximate 2m drop in water levels. This is, however, a confined system, so it is of great significance. There is a sudden decline in water levels, reaching a value of 15.86mbc in August 2017, before it recovers to resume the normal trend. This dip in water levels is most likely linked to the activities of the Kropz Elandsfontein phosphate mine (at BG00145), but this cannot be confirmed, due to a lack of information from the mine. The data should be re-evaluated once the legal proceedings for acquiring the data is completed.

Another explanation can potentially be the higher abstraction at the Langebaan Road wellfield. This would mean a time lag of only a month or two compared to the one of two years when the wellfield become operational in 1999. This dip in the normal trend of the water levels can be seen in a number of boreholes in the Elandsfontein aquifer unit and was even observed in some of the Langebaan Road aquifer unit boreholes. The time period when it was measured differed between the boreholes. The ideal would be to compare this data with the monitoring data from the mine and their activities on site, as well as the abstraction at the wellfield. Another unusual drop in water levels occurred after May 2019. No explanation can be provided for this change in the trend of the curve.

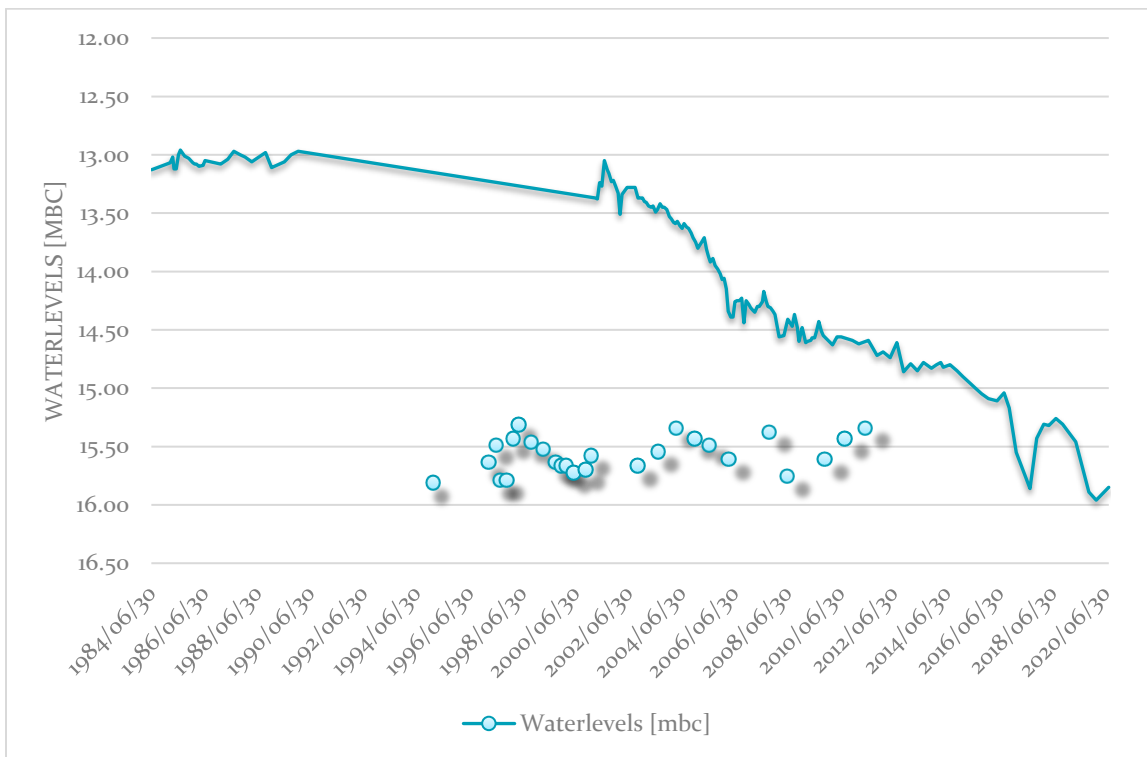


Figure 94: Time series graph of water levels for G33317 with cumulative deviation from mean.

Figure 95 shows the water levels per hydrological year on the background of historical water levels for G33317. The water levels for 2007 and onwards are all on the lower part of the historical background, with the 2007 curve the highest, and successive years moving lower till the 2017 curve that is almost completely below the historical record. This is of great concern, since it seems as if no recharge has taken place to this part of the aquifer system. The plots for the Langebaan Road aquifer show some recovery after the 2007-2009 cycle and again after the 2013-2014 cycle. The possibility exist that it would impact the flow of fresh water to the Geelbek area of the Langebaan Lagoon, with long-term implications for the unique characteristics of the area.

It is thus important to find out the flow of groundwater between the different units and the natural recharge to the system. It is only in understanding the system better that it would be possible to

effectively and sustainably manage this complex interlinked system. It would then be possible to implement MAR to correct this decline in water levels.

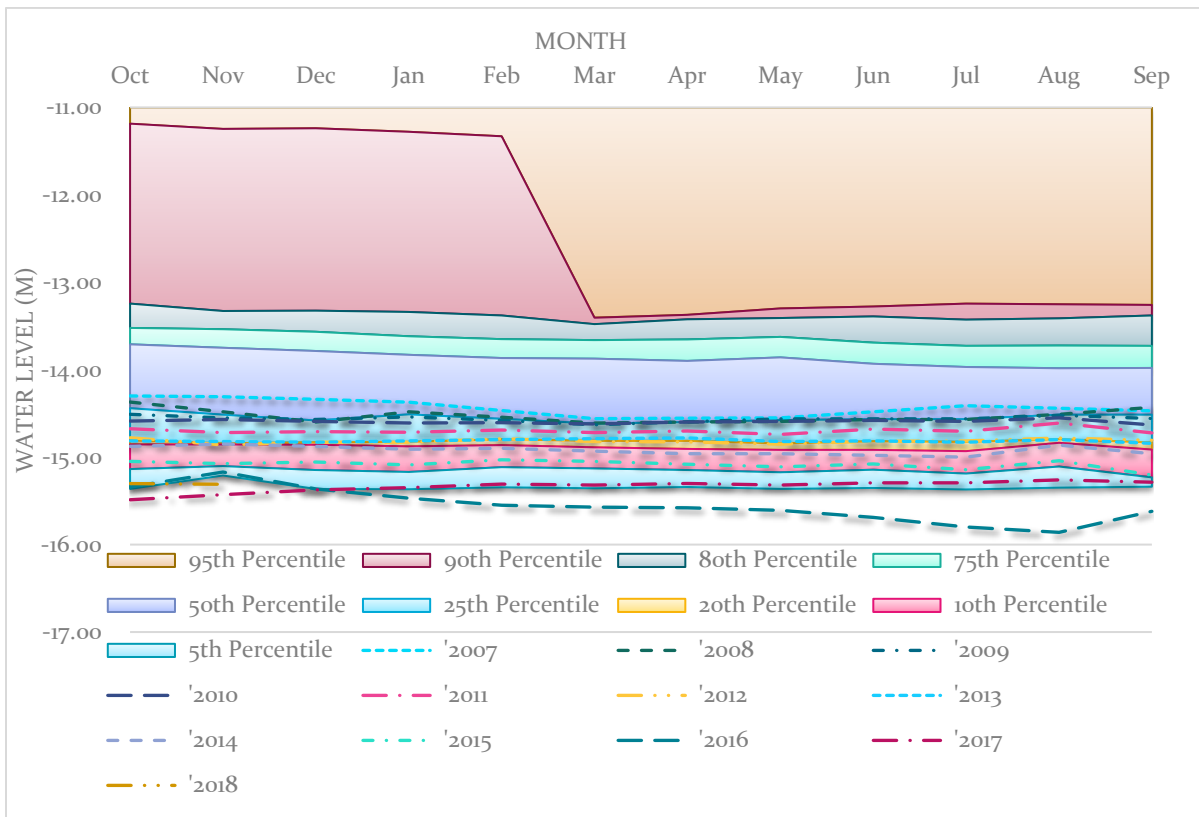


Figure 95: Graph showing the variation in water levels in a hydrological year for borehole G33317 on the historical background.

The water level curve in the groundwater level change index plot (Figure 96) shows a steady decline over time with a total drop of around 2m, with the downward spike in 2017 only very slight in this plot, but very clear with the level change indices.

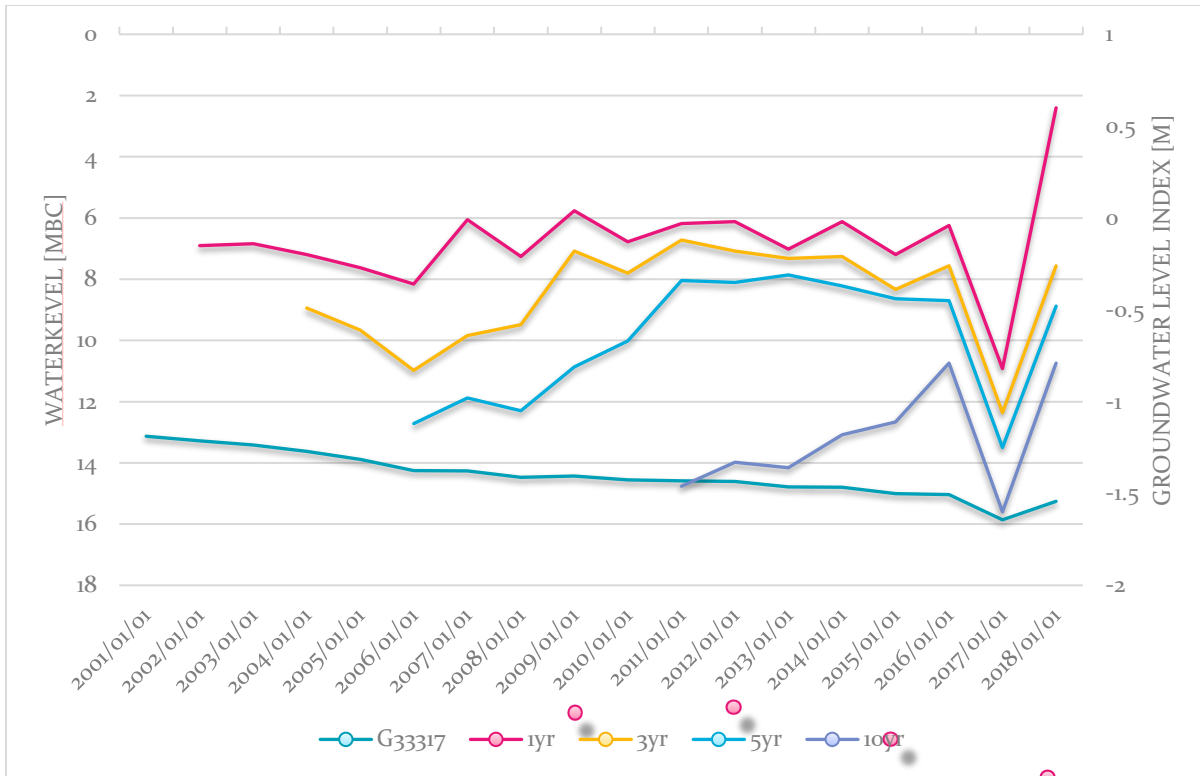


Figure 96: Groundwater level change index for borehole G33317 at 1-year, 3-year, 5-year and 10-year intervals.

BH1A is at the edge of the Langebaan Lagoon at Geelbek. It was drilled as part of a study into aquifer dependent ecosystems. It is in the upper unconfined layer and is part of a twin set of boreholes. The twin borehole that was drilled into the lower aquifer layer has to date not been found. DWS began monitoring the boreholes in 2013. The historical data has not been retrieved and could not be included in the analysis. The water levels show a seasonal fluctuation with a downward trend in the lower part of the curve (Figure 97). The same downward spike that was visible in G33317 in August 2017 is visible in this plot for March 2018. This is a seven months' delay in the response of the water levels over a distance of about 12km. If this spike is the result of the abstraction at the wellfield, it is the first time that the effect can be so clearly seen right up to the edge of the lagoon.

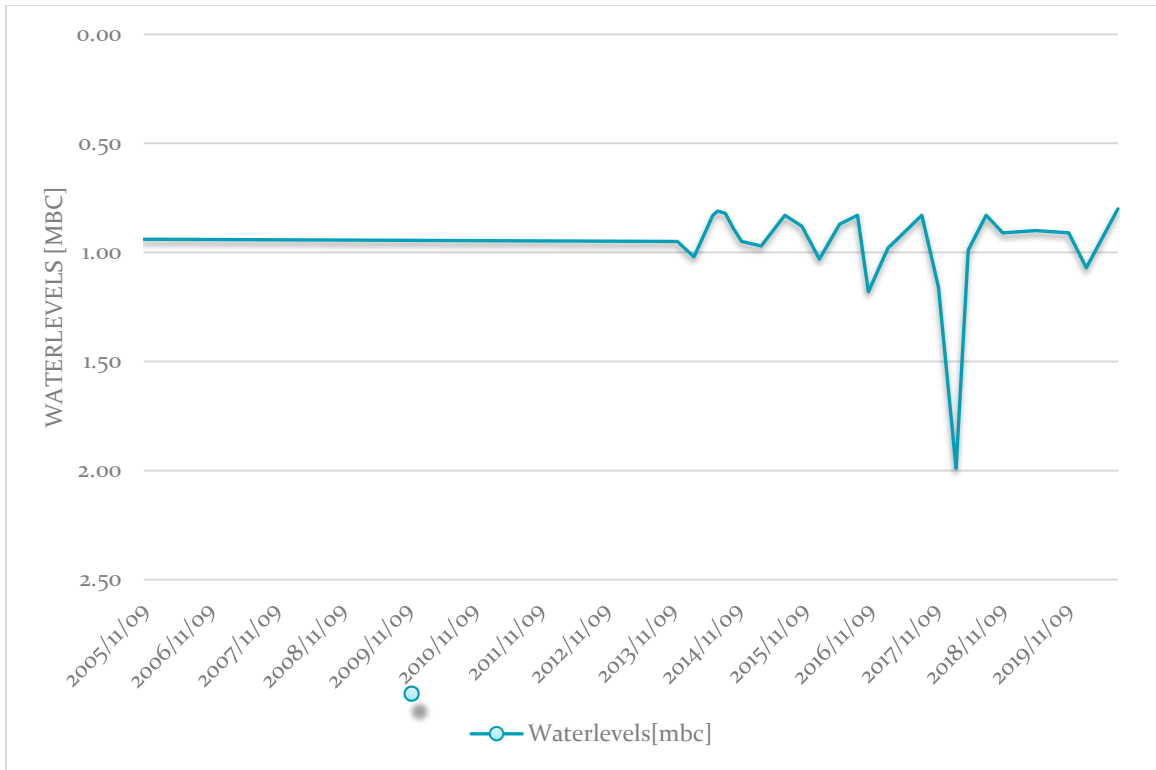


Figure 97: Time series graph of water levels for BH1A.

4.3.3 Adamboerskraal Aquifer Unit

The Adamboerskraal aquifer unit is to the north of the Berg River and borders on the Piketberg mountains. Only one investigation was done on this aquifer unit in 1984 by K.M.G. Timmerman (1985). Only four of these points now form part of the monitoring with a number of points from other projects added (See Figure 98 for a distribution of monitoring points).

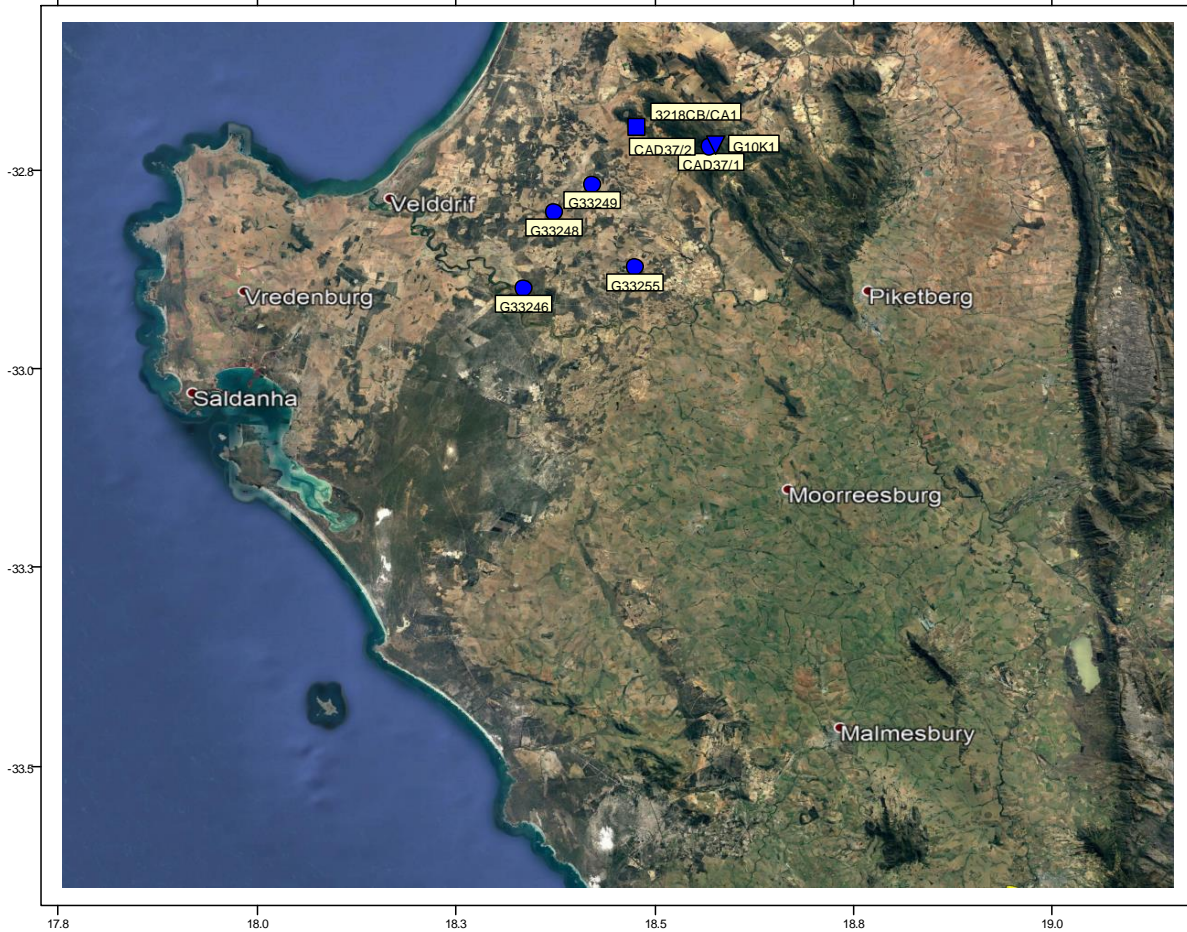


Figure 98: Satellite image showing the distribution of monitoring points for the Adamboerskraal aquifer unit (WISH; Lukas, 2012).

Borehole 37/2 is not in the Adamboerskraal aquifer unit but forms part of the monitoring in an effort to see if there is a link between the TMG aquifer of the Piketberg mountains. The water level graph (Figure 99) shows seasonal fluctuations. The effects of the drought can be seen in the downward trend of the water levels from November 2013 to May 2016, with an almost 8m drop in the water levels. This area had good rainfall in 2016, as reflected in the water levels.



Figure 99: Time series graph of water levels for 37/2.

Borehole G33255 is on the farm Harde Valley, in the area identified by Timmerman (1985b) for possible wellfield development. The graph for borehole G33255 shows natural seasonal patterns till May 2010 (See Figure 100). After this, the impact of nearby abstraction can be seen on the water levels, with a variation in water levels of almost 9m. The lowest water level was measured on 2016/02/23 with a reading of 13.56mbc, with the reading of June 2018 coming close. The depth of this response to the nearby abstraction may be an indication of confining conditions and a higher conductivity of the sedimentary deposits. The impact of the drought could be clearly seen in the drop of water levels as a result of lower rainfall, higher temperatures and greater abstraction to compensate for this.

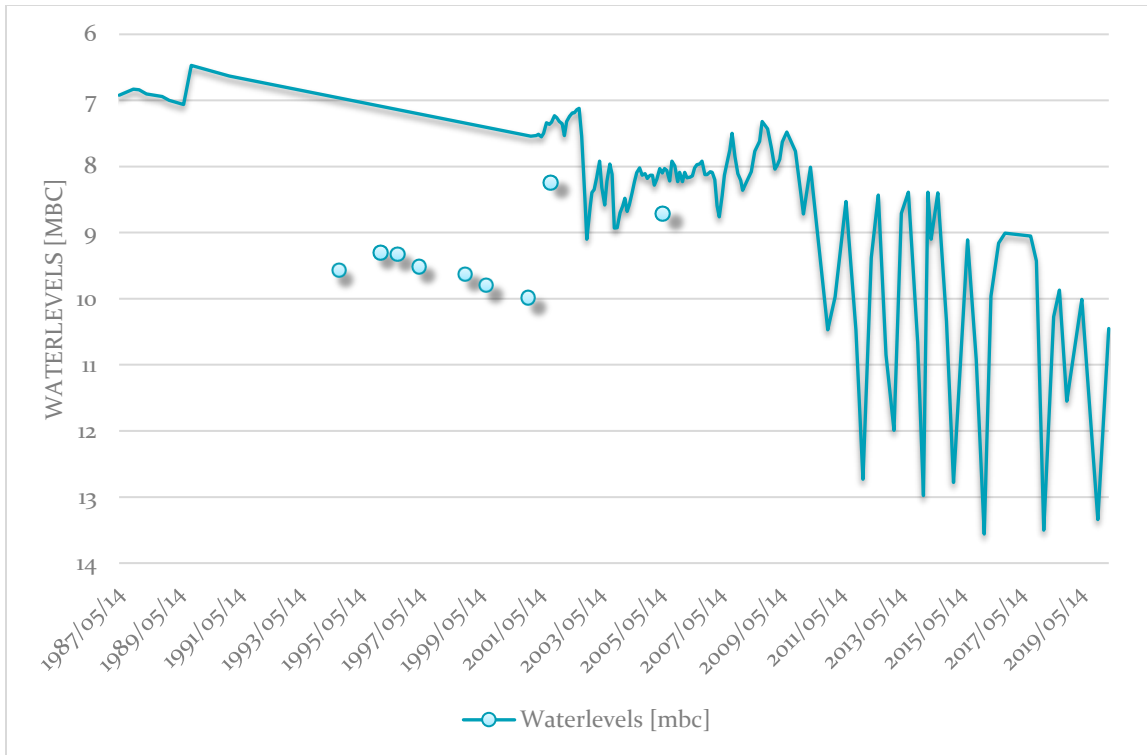


Figure 100: Time series graph of water levels for G33255 with cumulative deviation from mean.

G33246 is on the farm Kersefontein, next to the Berg River. The water level graph (Figure 101) looks very similar to that of boreholes on the other side of the river (See Figure 78 for comparison) with the big recharge event in 2007, followed by the 2008-2009 peaks, and the response to the good rainfall in 2013-2014. It shows seasonal fluctuations that can be linked to longer cycles. The drought can be seen in the water level measurements in 2016 to 2018.



Figure 101: Time series graph of water levels for G33246 with cumulative deviation from mean.

4.3.4 Grootwater Aquifer Unit

The Grootwater aquifer unit is along the coast with the R27 running through the middle. Figure 102 shows the distribution of the monitoring points. The points around Darling are not in the Grootwater aquifer unit, but it monitors the Colenso Fault system.

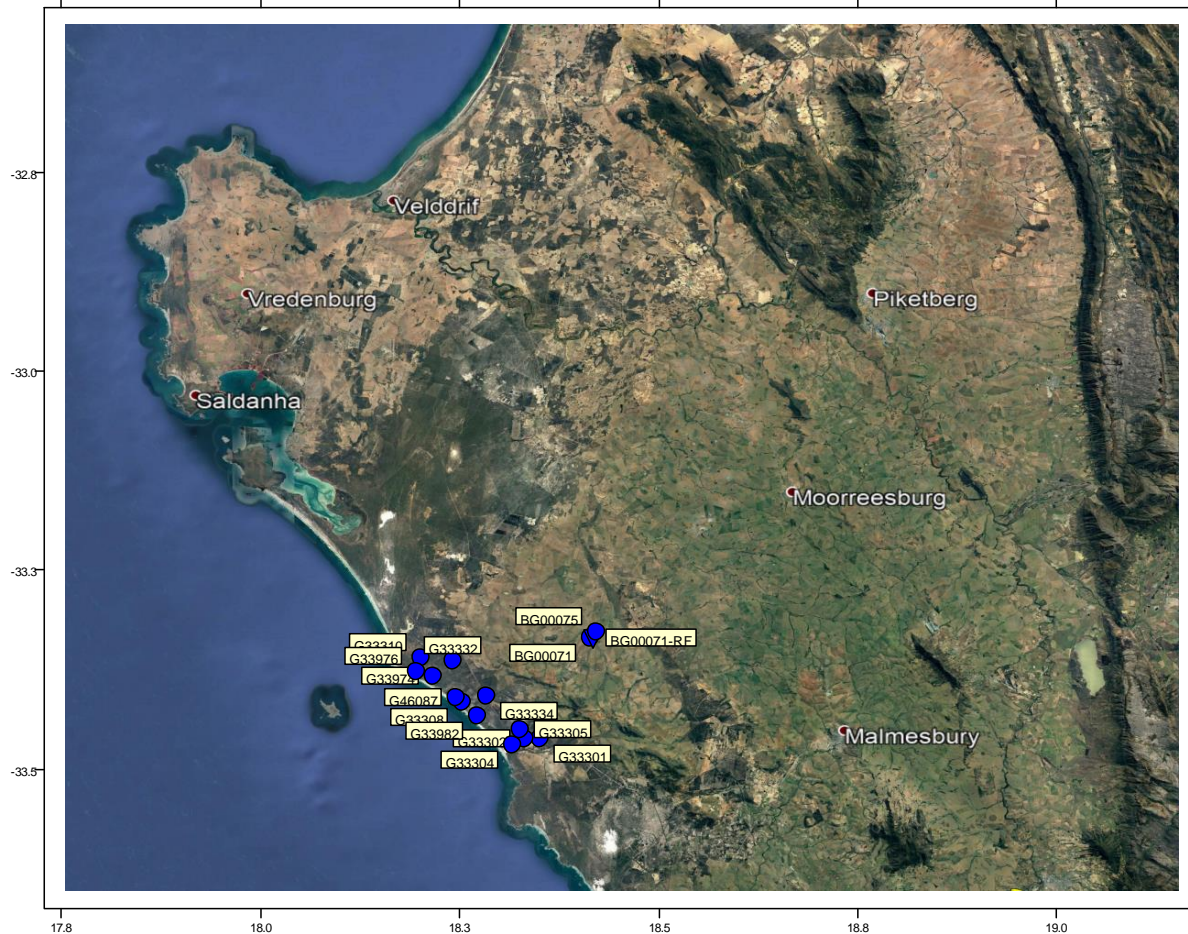


Figure 102: Satellite image showing the distribution of a selection of monitoring points for the Grootwater aquifer unit (WISH; Lukas, 2012).

G33331 is a borehole with four multilevel piezometers. It is on the original farm Grootwater and is part of a pumping test set-up (one of three on the Grootwater aquifer unit). G33332 was the test borehole, with G33309 and G33331 as the observation boreholes. The water levels of these piezometers are quite close, as can be seen in the plot Figure 103. The water levels have not been corrected for the difference in height between the four piezometers. The behaviour of the different water level records are very similar with seasonal trends. They also respond to the rainfall cycles, with good recharge in 1987-1989, 2001, 2007-2009, and again in 2014. The recharge events change the water levels with between 1 and 2m at a time. It is not clear where the recharge for this aquifer comes from yet, but it needs to be significant to make such a big difference in a semi-confined system. The most likely local source would be the Darling hills.

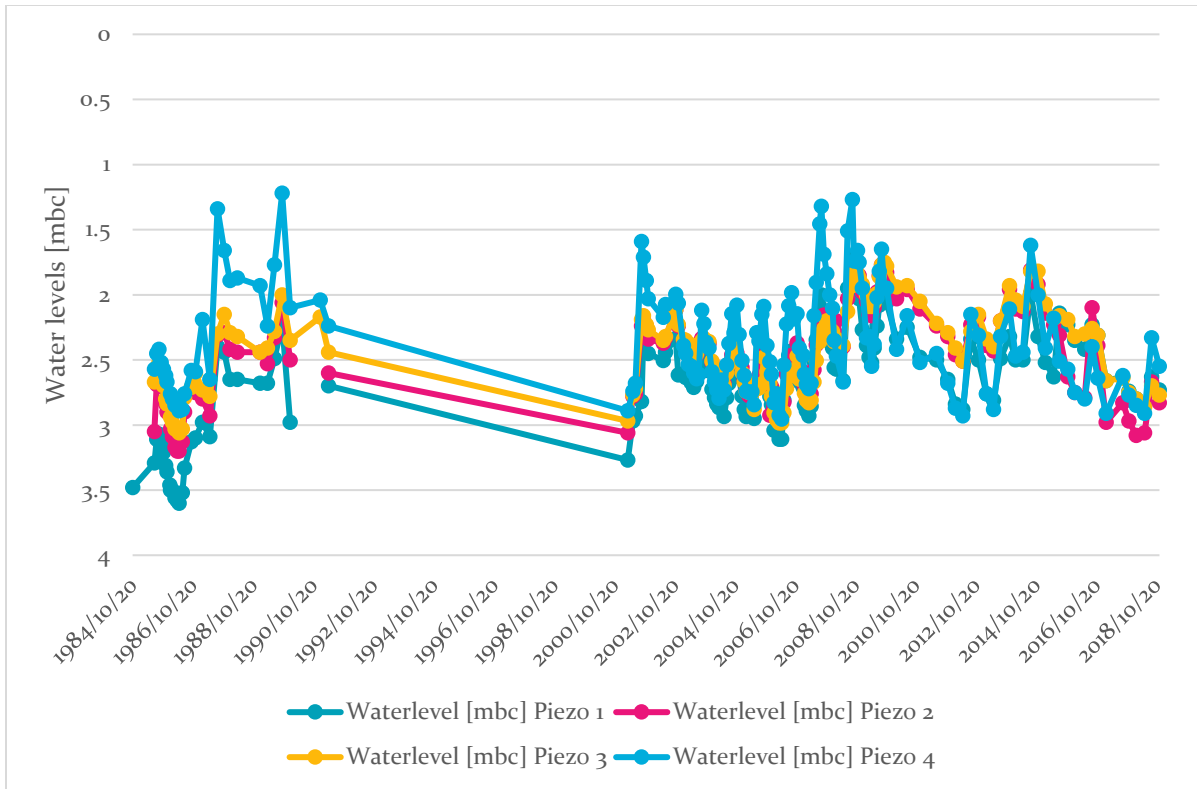


Figure 103: Time series graph of water levels for the four piezometers of G33331.

G33333 is another multipiezometer borehole that is part of a pumping test group on the farm Vygevallei. This borehole had 3 piezometers but the shallowest one had collapsed shortly after construction. G33334 was the test borehole, and it is currently equipped with a pump and provides water for household and commercial use. G33307 complete the set of observation boreholes and was only found recently with the removal of a dense stand of port jacksons.

Piezometer 3 shows the effect of the abstraction at G33334 (See Figure 104), while piezometer 1 have a slight seasonal trend. Both of these piezometers are in a semi-confined to confined system. The fact that piezometer 1 are not affected by the nearby abstraction shows that the two layers are not hydrologically linked. These piezometers do not seem to react to the recharge events like G33331 and G33304.

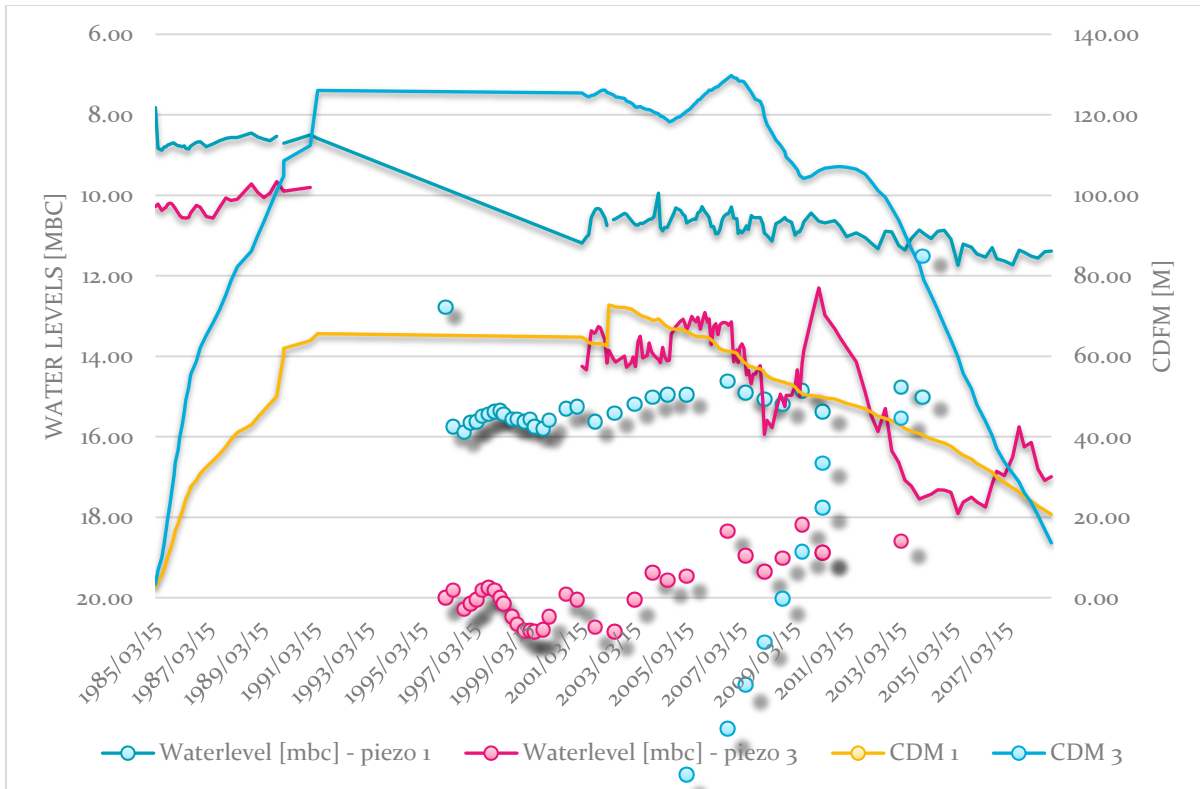


Figure 104: Time series graph of water levels for both piezometers of G33333 with cumulative deviation from mean.

The removal of Port Jacksons on the farm Kransduinen led to the discovery of a number of boreholes, but the pumping test set-up has not been found yet. G33304 is next to the R27 and adjacent to the Modder River. It is thus the first borehole of the Grootwater aquifer unit that will be encountered when travelling along the R27 from Cape Town. The water levels show a seasonal cycle (Figure 105) with recharge events linked to periods of increased rainfall: 1987-1989, 2001, 2007-2009 and 2013-2014. The CDM curve tends to mimic these periods, with a two to three-year delay between the peak in the water levels and the peak in the CDM curve. The impact of the drought can be observed in the water levels of the last four years.

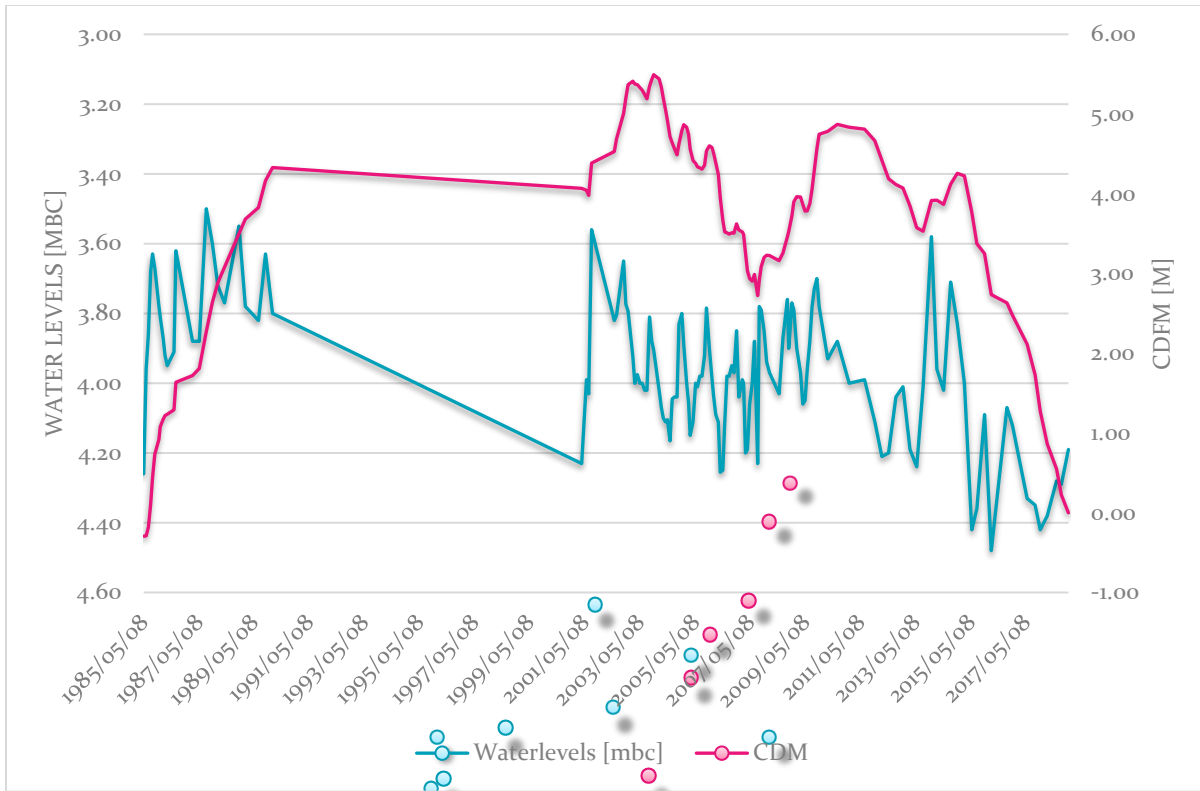


Figure 105: Time series graph of water levels for G33304 with cumulative deviation from mean.

Correlation of water levels with rainfall

Figure 106 shows the water levels for G33304 and the two piezometers of G33333 with rainfall as measures at Jakkalsfontein (private) and Geelbek (SAWS). There seems to be a correlation between rainfall and the response in water levels for G33304 and piezometer 1 of G33333, but there is a time lag of about six months.

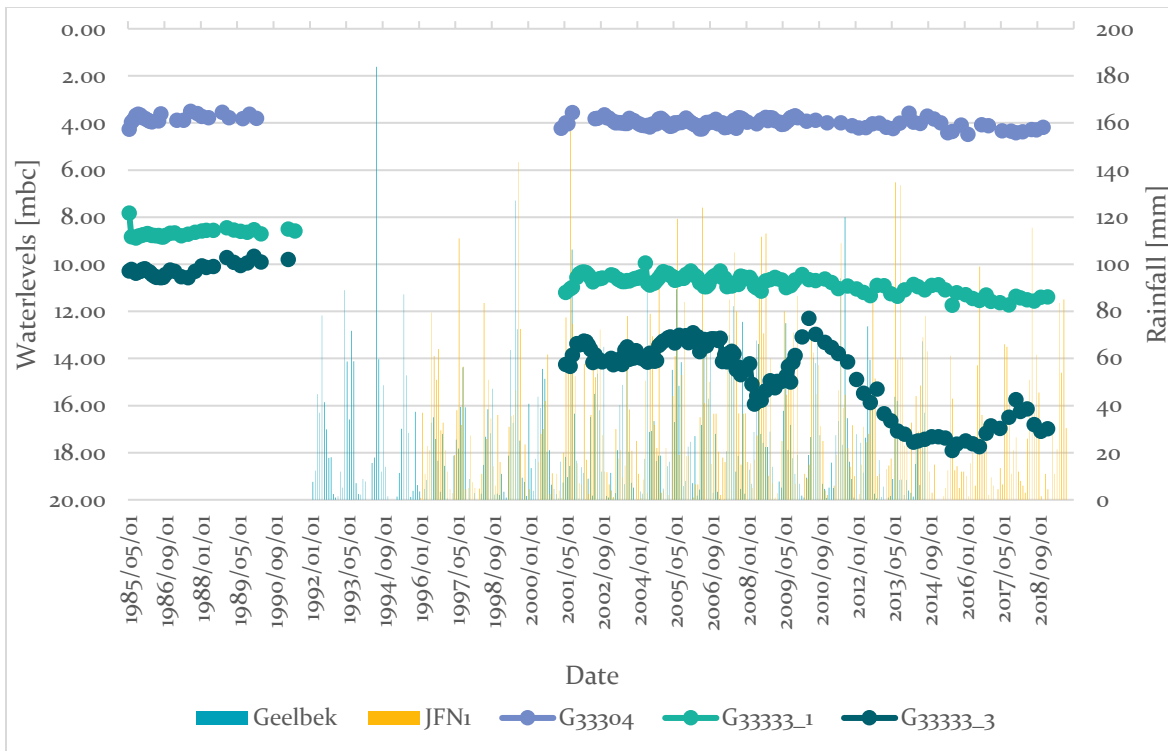


Figure 106: Water levels for G33333-VL1, G33333-VL2 and G33304 with rainfall at Jakkalsfontein and Geelbek.

Yesertener (2008) used the CDM of rainfall against water levels to determine whether the abstraction is sustainable. Initial analysis by Vermaak, et al., (2017) concluded that this method does not work in some with semi-confined to confined systems. It may also prove a problem when the bulk of the recharge is not direct recharge, due to the time delay (see Figure 107). A second look at the method (Figure 108) shows that it may be valid in semi-confined to confined systems, with the water levels of G33333-VL3 fitting closely to the CDM curve for Geelbek. It is interesting to note that Geelbek is about 30km to the north of Vygevallei and that is would thus have a very small role to play in the recharge of the aquifer. The fit with the CDM curve for Jakkalsfontein is not as good, but it shows that it is possible to use the method in a South African situation with complex aquifer systems.

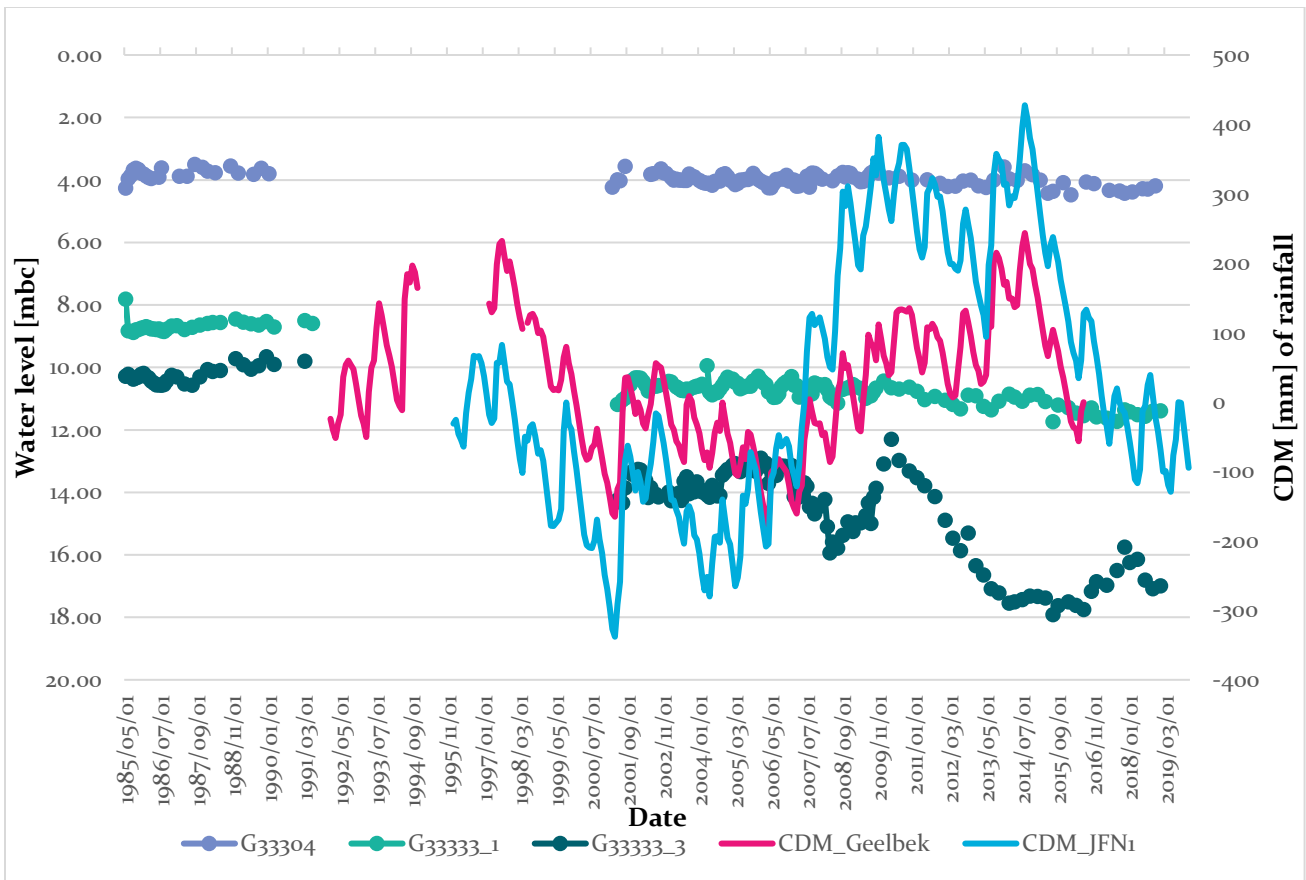


Figure 107: Time series graphs of water levels for G33333 and G33304 with CDM of rainfall.

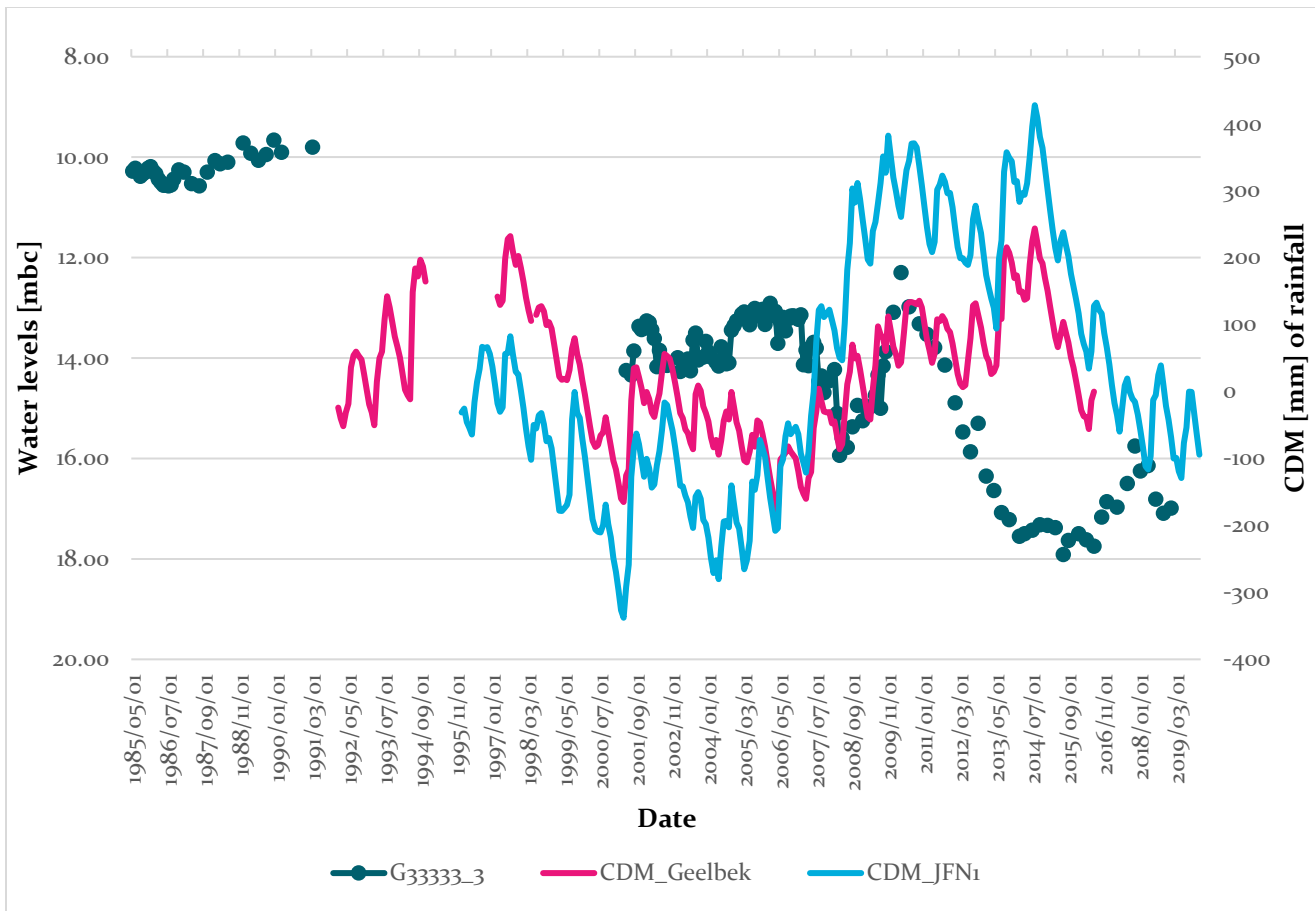


Figure 108: Water levels for G33333-VL3 with the CDM curves of rainfall.

4.4 Yield estimations, storage potential and flow

Yield estimations and storage potential was discussed in chapter 3. Nothing can at this stage be added to the yield estimations and storage potential of the Lower Berg River Aquifer System. There are still too many questions and unknowns to have proper concept of these parameters. It will for all intents and purposes be estimates, of which the ones by Timmerman (1985b) are as good as any that came after him. The yield and storage potential are functions of the sedimentary deposits from which the abstraction takes place and where the groundwater is stored, and it will differ over short distances. It is thus difficult to determine a yield or storage potential that would be true for an aquifer unit, if not more so for the whole aquifer system.

The stable isotope, tritium and carbon-14 analysis by Andries (2019) and the work by Smith (2016) have shown that the flow in the Langebaan Road and Elandsfontein aquifer units are towards the coast, flowing towards Saldanha Bay and the Langebaan Lagoon at Geelbek respectively. It was also demonstrated by the various models for the area (Smith, 2016; Seyler, 2016; DWA, 2008).

4.5 Hydrochemistry

4.5.1 Rainfall

The electrical conductivity (EC) of the rainfall samples were all low, mostly below 10mS/m, with the concentration of all the chemical were usually low as well. The results were plotted on a Piper diagram (Figure 109) and Stiff plots (Figure 110) in order to compare it to the groundwater chemistry results. BG00074-RF did not plot, as a result of gaps in the parameters analyzed. There is not clear pattern to the distribution of the points on the Piper diagramme. This may be related to the season when the sample were taken, or the year. If it was a low rainfall period, it is possible that the chemical constituents may be more concentrated. The first rainfall of the season will also potentially have the highest concentrations. The proximity to the coast may also influence the salt content of the rainfall samples. One of the drawbacks of the cumulative rain gauges, is that birds like to perch on them. The consequence of this is bird droppings that contaminate the rainfall samples, increasing the ammonia content.

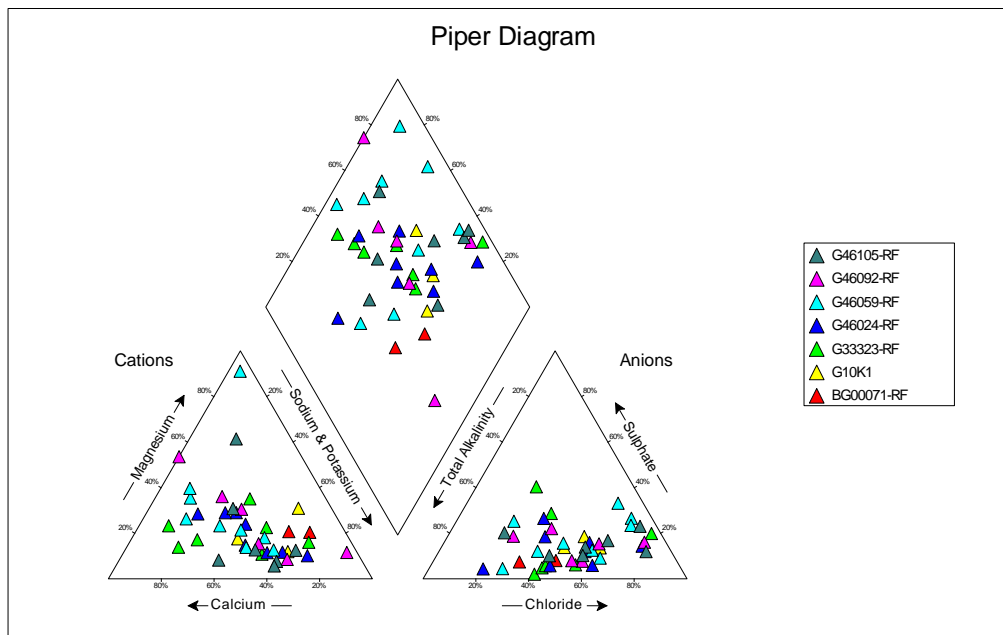


Figure 109: Piper diagramme for the chemistry analysis of the cumulative rain gauges in the study area (generated with WISH; Lukas, 2012).

G10K1 is the furthest inland and at the highest elevation in the mountains north of Aurora. All the constituents on the Stiff plot are low, with sodium and chloride being the dominant ions. G33323-RF is in the floodplain of the Berg River and at a low altitude. It is also still in the tidal zone of the of the river which could contribute to its higher salt content. Its highest ion concentrations are for sodium and chloride, followed by magnesium and sulfate. G46024-RF usually records the highest rainfall after G10K1. It is close to Hopefield in an area with a higher elevation than G33323-RF. It is thought that the local recharge may be coming from the dunefields around G46024-RF

because of its higher elevation. Its EC is the lowest of all the rain gauges, together with G46059-RF. Unlike the previous two rain gauges discussed, its major ions are calcium and bicarbonate. G46105-RF is at the Langebaan Road wellfield and is in a bit of a basin surrounded by higher lying dunes and granite outcrops. The major ions are sodium and chloride. G46059-RF is north of the wellfield, but usually records higher rainfall. Its salt content is higher, with the major ions being sodium and chloride. BGo0071-RF is the furthest south, just north of Darling. The highest ion concentrations are bicarbonate, chloride and sodium. The rain gauge is surrounded by granite outcrops on the southern side, which may affect the quality of the rainwater. BGo0074-RF is between BGo0071-RF and the Langebaan Road cluster. No Stiff plot is available for this rain gauge as a result of incomplete data sets. G46092-RF is the closest to the coast on a low elevation. It has the highest salt content according to the Stiff plot. The highest ion concentration is for bicarbonate, followed by sodium and chloride. There is a lot of calcrete in the area and recent road building activities might have influenced the quality.

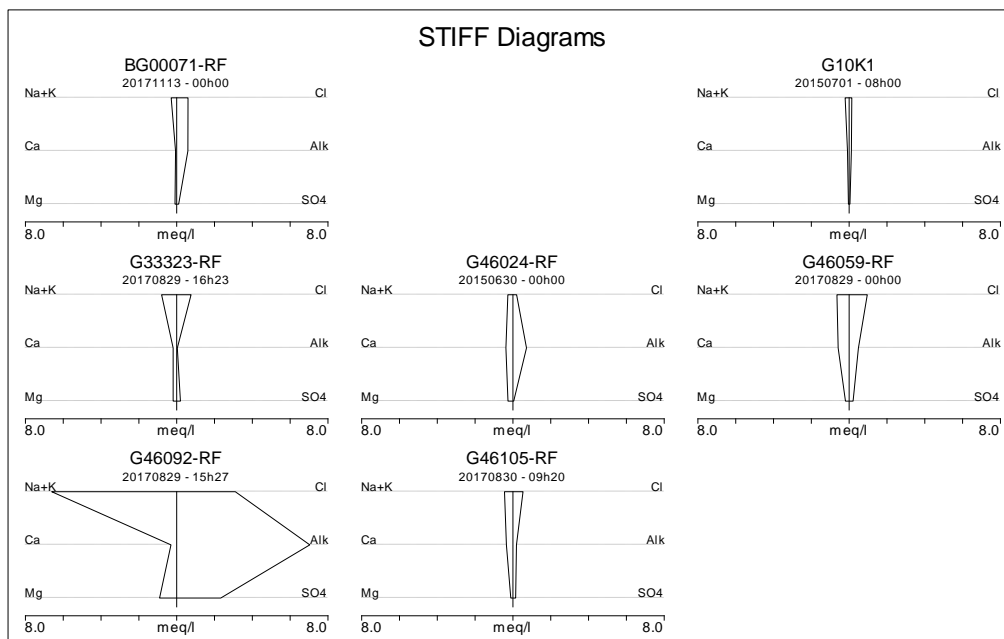


Figure 110: Stiff plots for the chemistry results of the last data record for the cumulative rain gauges (generated with WISH; Lukas, 2012).

4.5.2 Surface water

Water samples were taken at the bridge near the farm Kersefontein and three samples sent in for chemical analysis. The EC field readings fluctuates during the year with a value of 3520mS/m measured in February 2018 and 243mS/m measured in August 2018. The dominant ions are sodium and chloride (See Figure 111 for the Piper diagram and Figure 112 for the Stiff plot), which correlates with the fact that the sampling point is within the tidal zone of the river.

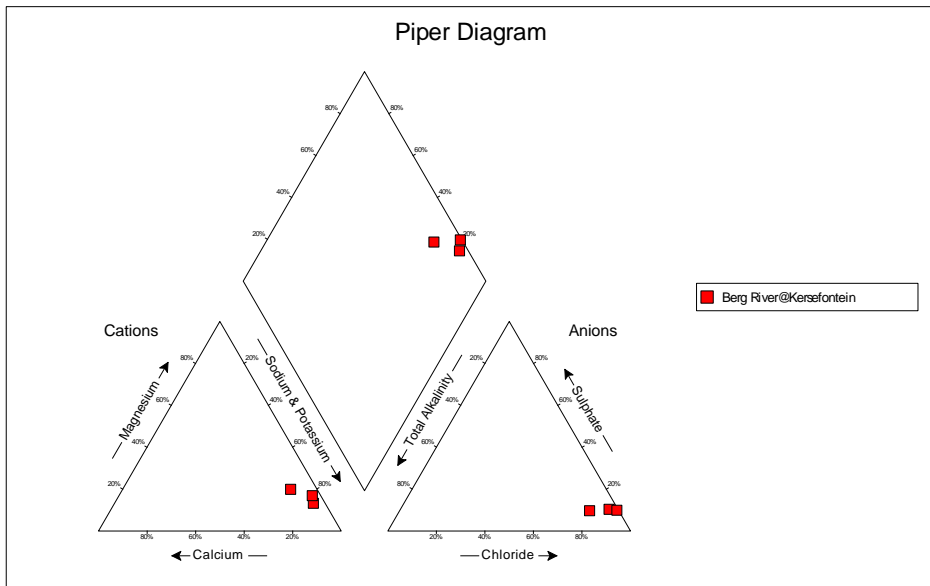


Figure 111: Piper diagram for samples from the Berg River taken at the Kersefontein bridge (generated with WISH; Lukas, 2012).

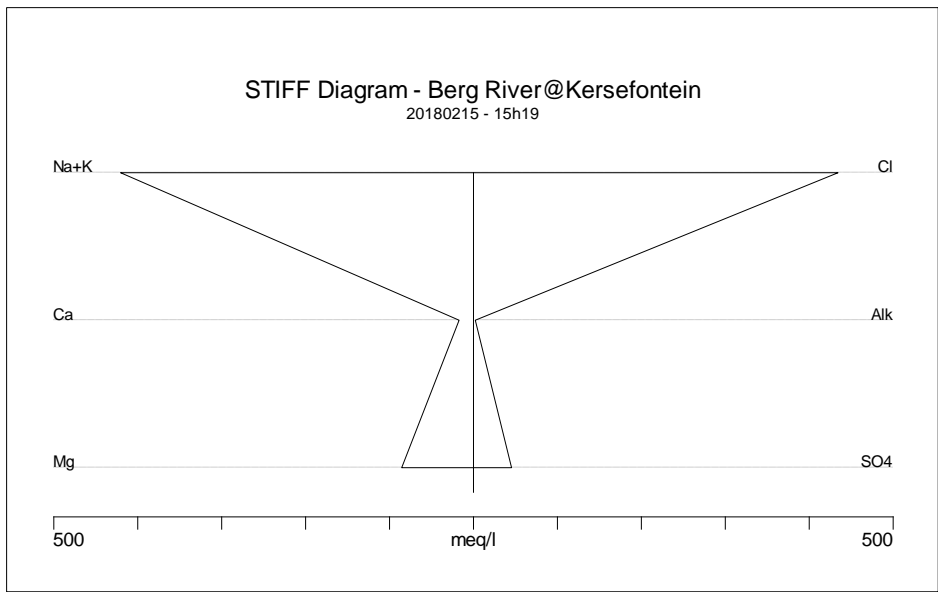


Figure 112: Stiff diagram for the water chemistry at the Kersefontein bridge over the Berg River (generated with WISH; Lukas, 2012).

4.5.3 Groundwater

A first rough analysis of the groundwater chemistry was done in 2009 when DWS still monitored the water quality in 42 boreholes (Vermaak, 2009). This number has been reduced to 25 in 2010,

with the bulk of the monitoring for the Langebaan Road aquifer unit. Water quality monitoring points has since been added for the Grootwater, Elandsfontein and Adamboerskraal aquifer units.

Figure 113 give an indication of where the monitoring points where water quality was sampled before 2010 on the Langebaan Road aquifer unit are situated. These points have a long data record of water quality. Table 1 in the Appendices gives the coordinates and the different numbers for the monitoring points that was used in the original 2009 analysis.

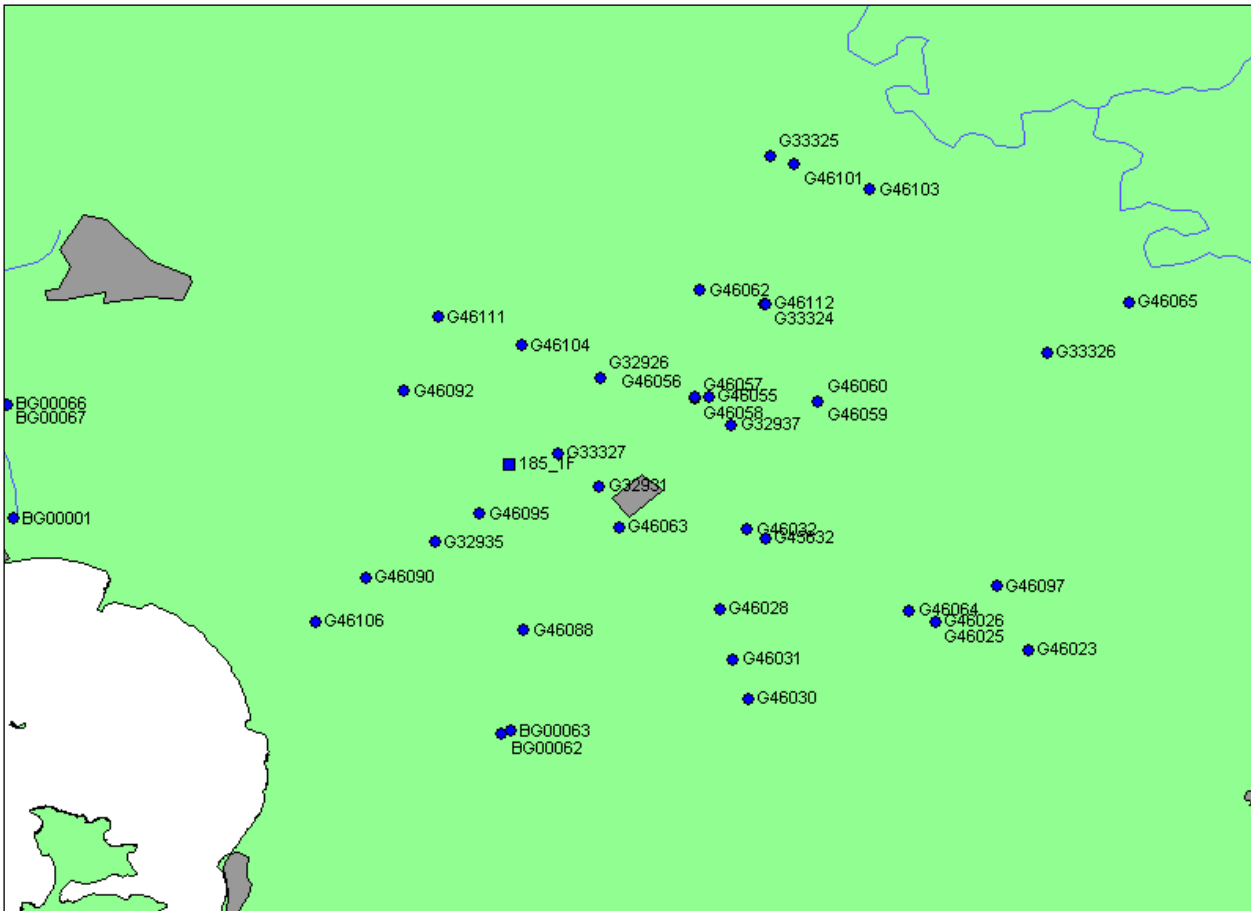


Figure 113: Distribution of monitoring points on the Langebaan Road aquifer unit (42 of the 47 sampling points sampled regularly before 2010).

The Piper diagramme in Figure 114 shows the chemical composition of representative points in the Adamboerskraal area. Borehole 37/1 (marked CAD_{37/1} on the plot) represents a borehole at the top of the mountain above Aurora. It is thus in the TMG aquifer. This borehole shows a similar chemical character as that of the rainfall collected from G10K1. The geosite 3218CB/CA₁ is a spring just outside Aurora that originates at the foot of the mountain, and as such represents TMG aquifer water. The position of the data points for the spring water (3218CB/CA₁) is in the same area as GEOSS-A7 and GEOSS-A12, which most probably also represents mostly TMG water. They are boreholes at the foot of the mountain. The data points for borehole G33249 lie to the bottom of

the previous cluster, while those of G33255 almost forms a cluster of their own even lower down on the diamond, with the high concentrations of sodium, chloride, magnesium and alkalinity.

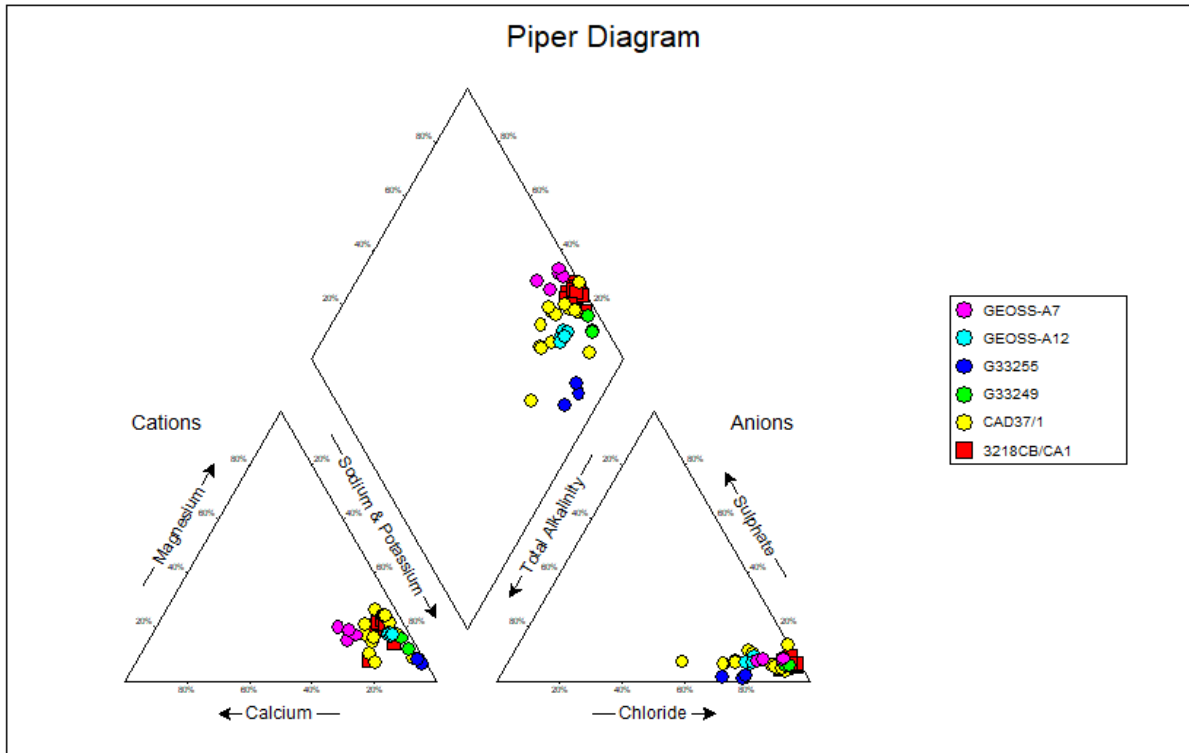


Figure 114: Piper diagram for the monitoring points in the Adamboerskraal monitoring route (generated with WISH; Lukas, 2012).

There seems to be a gradual change in the shapes of the Stiff plots in the following sequence: 37/1 (TMG), GEOSS-A7 (TMG), 3218CB/CA1 (TMG), GEOSS-A12, G33255 and G33249 (Figure 115). This most probably shows the change from TMG type water – where very little interaction takes place between the rock formations and the water – to the coastal aquifer unit overlying Malmesbury shale. The Stiff plot for GEOSS-A7 shows the closest resemblance to that of 37/1. It is located above 3218CB/CA1 (Figure 116). The Stiff plots of G33255 and GEOSS-A12 have a similar shape, with a slightly higher sodium and chloride dominance in G33255. This could be an indication that these boreholes are located in the same palaeochannel (see Figure 116). G33249 seems to be in a different palaeochannel, as the pattern of the Stiff plot is very different from the others. It is possible that this site is in the same palaeochannel as G33248 and G33246. The dominant ions are sodium and chloride for all the geosites.

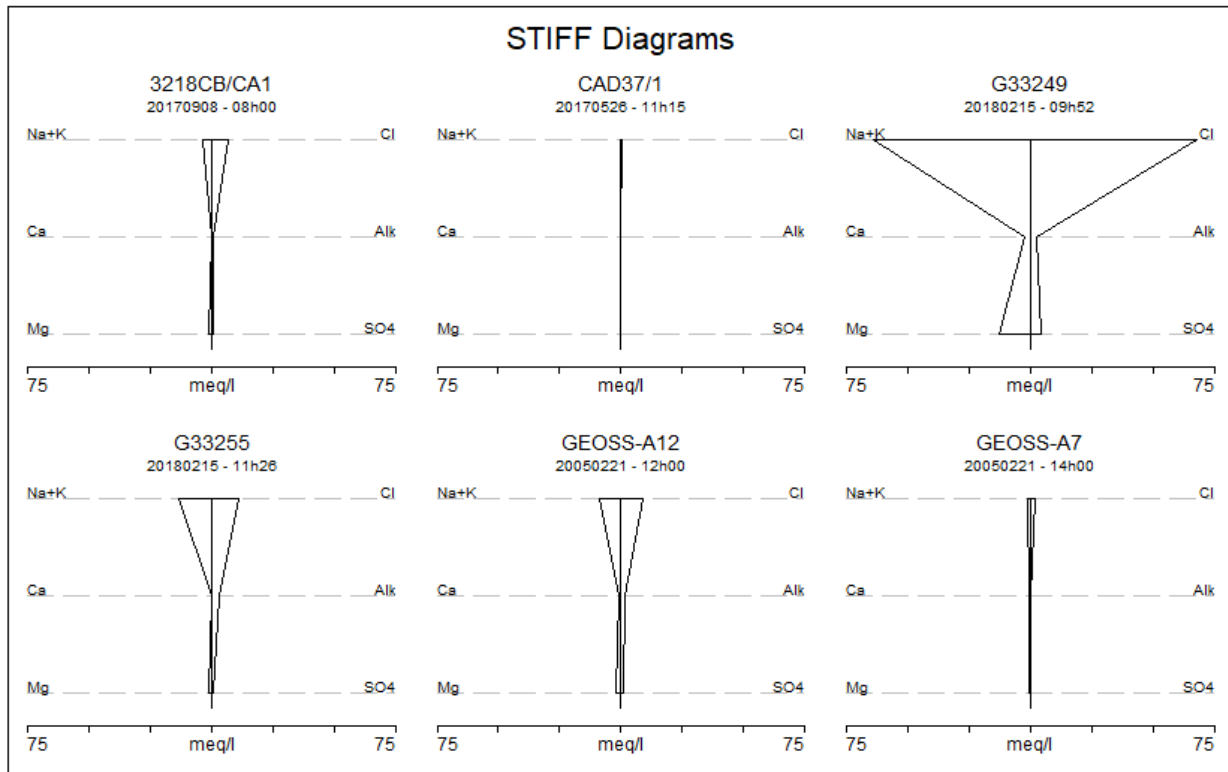


Figure 115: Stiff plots for the water quality of the geosites in the Adamboerskraal area (generated with WISH; Lukas, 2012).

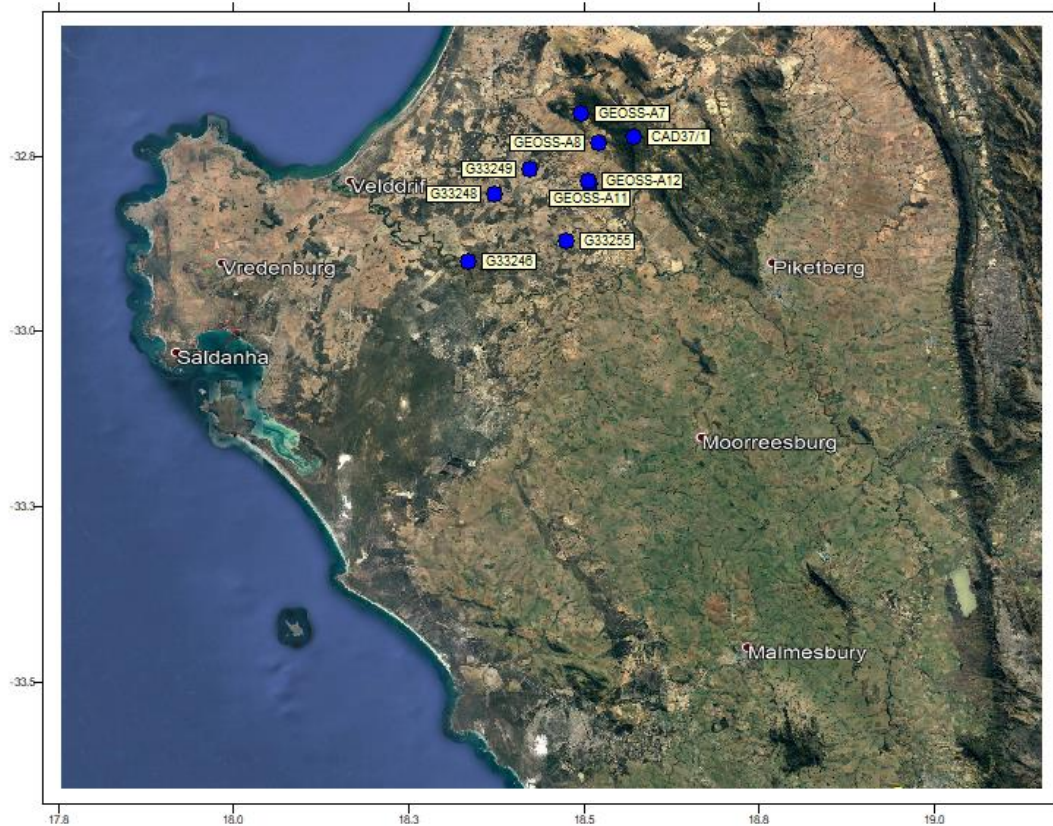


Figure 116: Satellite image showing water quality data points for the Adamboerskraal area.

The Piper diagramme (Figure 117) indicate that the most dominant groundwater type for the Langebaan Road aquifer unit is chloride-sodium water, with most of the data points forming a cluster. There is a number of samples that tends towards the bicarbonate-calcium water type, which could be as a result of the calcrete in the area. Magnesium and sulphate concentrations are generally low, with a few exceptions that was found during the PhreeqC analysis and some of the Stiff plots.

There seems to be a bit of a progression with the boreholes upgradient in the palaeochannel plotting more towards the middle of the diamond field and those closer to the coast plotting at the right-hand side. BG00058 seems to be the exception to this, as it is an artesian borehole in the middle of an old mining excavation at the West Coast Fossil Park. It is in its own cluster, lower than the main line of the other data points. G46105 is in the basement aquifer, which in this case is Malmesbury shale. It forms its own cluster below the main cluster. There is one outlier for BG00136 in the anion triangle, that shows high levels of sulphate. This may be due to the presence of peat in the area and the fact that the borehole had not been in use since 2009. Sampling at the borehole only started again in 2015.

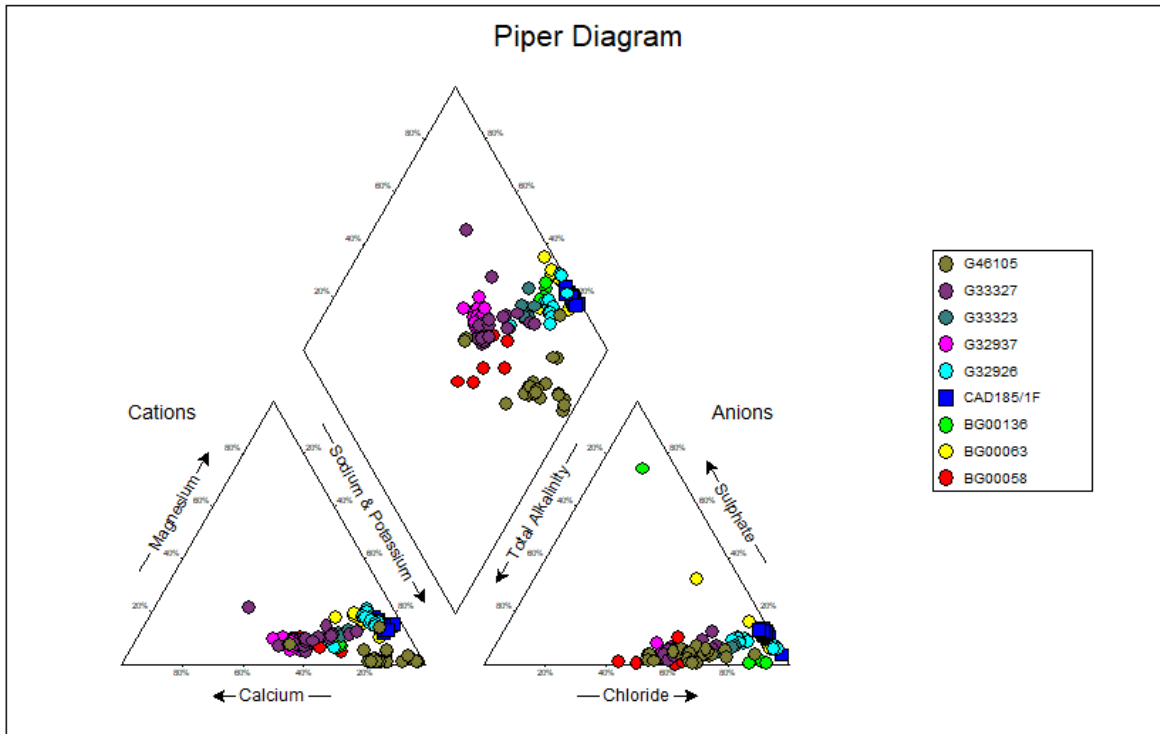


Figure 117: Piper diagramme for the representative points in the Langebaan Road area (generated with WISH; Lukas, 2012).

Figure 118 shows the Stiff plots for representative geosites in the Langebaan Road aquifer unit. G33323 is closest to the Berg River and shows direct recharge from either rainfall or the river. The water is of a sodium-chloride type with fairly high concentrations. It may potentially be affected by evapotranspiration, since it is in the unconfined layer of the aquifer unit. This point is about 13km northeast of the wellfield. When comparing the Stiff plot of this borehole with the Stiff plots for the boreholes at or around the wellfield, there must have been some natural treatment taking place to reduce the salt content of the water. It may also be an indication that there may be recharge from another source that helped to dilute the salt content. BG00136 is the injection borehole for the MAR test that was done in 2008 and 2009, while G46105 is the basement aquifer borehole at the wellfield. Boreholes G32926 and G32937 are both towards the northwest of the wellfield, with G32937 having a tendency to become artesian. It shows that there is a slight decline in water quality further from the wellfield (G32926 is further away from the wellfield than G32937). G33327 is just before the West Coast Fossil Park, closer to the wellfield and BG00058 is in one of the old quarries that made up the old Samancor phosphate mine that is now the West Coast Fossil Park. The Stiff plots for these two boreholes are similar, and closely resembles that of BG00136, G32937 and G46105. There is thus little change in water quality over a large area of the lower aquifer layer of the Langebaan Road aquifer unit. The water quality of 185/1F (CAD185/1F on the plot) is different from the two boreholes close to it. It is a surface water body inside one of the old quarries at the mine site that is green in colour and has an inflow of groundwater since it is below

the watertable. The EC that has been measured in this water body is around 5 000S/m, which gives an indication of the effects of evapotranspiration and possibly the salts that remained in the soil after the closure of the mine. The EC measured in the adjacent water body is in the vicinity of 17 000S/m. It has a pink colour and the soil surrounding the water is covered with a salt crust. There is potentially a lower groundwater inflow into this part of the quarries. BG00063 is a borehole that was drilled into the Colenso Fault System. Its water levels show a tidal pattern, and it shows a higher magnesium concentration than most of the other boreholes in the Langebaan Road aquifer unit. The Stiff plot also has a different shape, indicating that this borehole is not linked to the main aquifer unit.

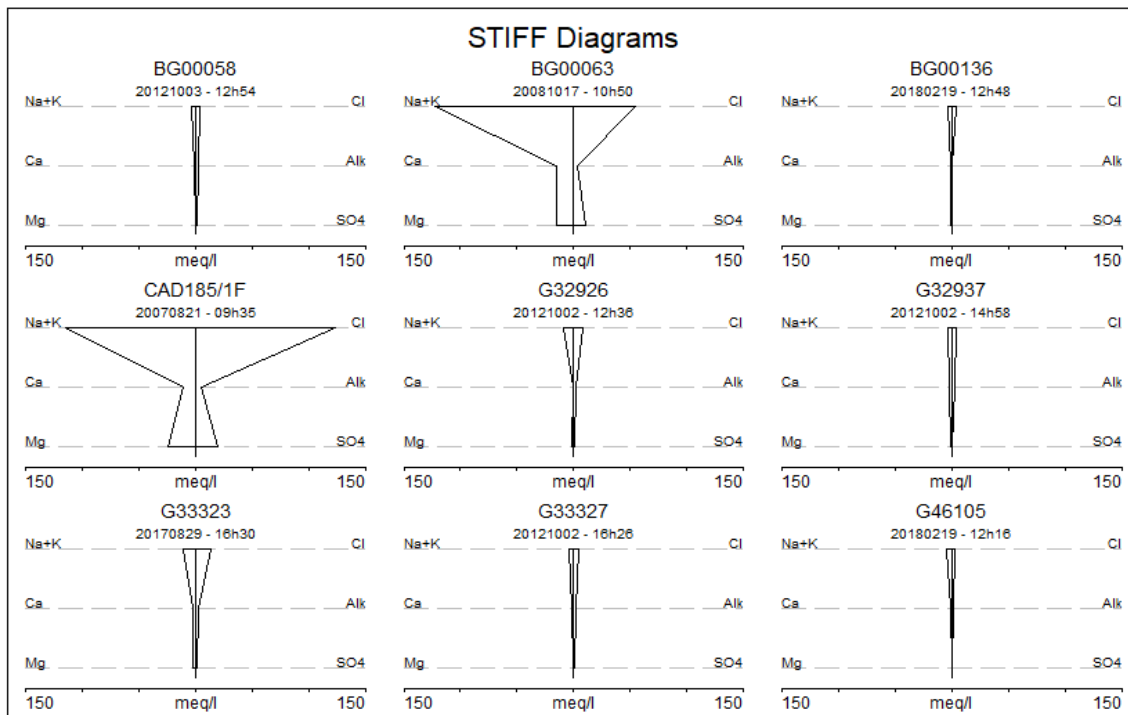


Figure 118: Stiff plots for representative boreholes in the Langebaan Road aquifer unit (generated with WISH; Lukas, 2012).

The water quality characteristics of the Elandsfontein aquifer units is different to that of Langebaan Road and Adamboerskraal aquifer units. There is a very strong calcium-bicarbonate characteristic in most of the data points (Figure 119) and this is also reflected in the Stiff plots (Figure 120). This could be an indication that this aquifer unit is closer to the recharge source, but it could also reflect the geology of the area. There are very prominent calcrete banks in some of the dunes and this can be seen in the borehole logs. The data points mainly form a cluster in the middle of the diamond with a few scattered outliers. G33320 is the furthest north of the geosites on the border between the Langebaan Road and Elandsfontein aquifer units. G33505B which is to the north of the aquifer unit, just south of G33320, forms its own cluster below the main cluster and G30925 its own cluster to the right. G30925 is closer to the coast than most of the boreholes (borehole BH1A and BH2A being the exceptions). BG00124 is on the farm Theefontein and is the

one furthest inland. Most of these boreholes is in the confined layer of the aquifer unit and shows that there is very little variation in the water quality over a large area of the aquifer unit.

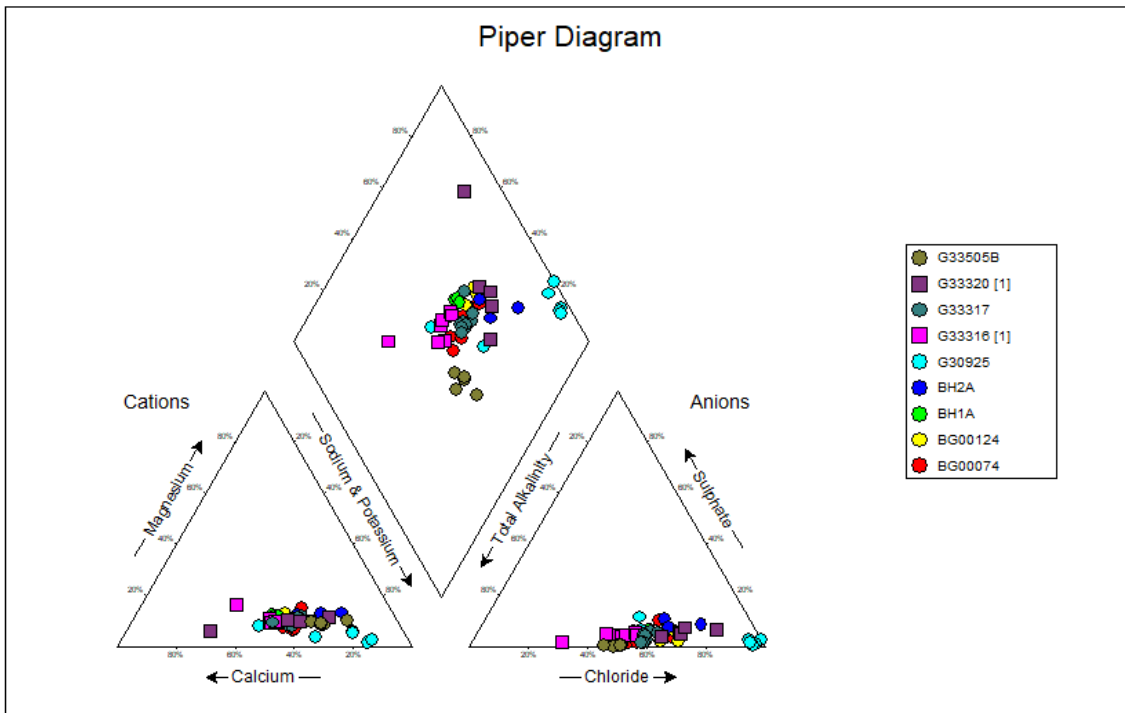


Figure 119: Piper diagramme with representative points for the Elandsfontein aquifer unit (generated with WISH; Lukas, 2012).

The Stiff plots of BG00074, BG00124, BH1A, G33316(1), G33317, G33320(1) and G33505B shows similar shapes, providing an indication that these boreholes are all in the same groundwater system (See Figure 120). There is a very high calcium-bicarbonate component to the sodium-chloride type water found in this aquifer unit. G30925 has a much smaller calcium-bicarbonate component, despite the fact that it is in a high dune with calcrete and sand layers. Its proximity to the coast and exposure to salt spray from the ocean may contribute to the high sodium-chloride signature. The Stiff plot of BH2A provides an indication that the borehole is in a different groundwater system or exposed to different conditions. It is to the south of the Langebaan Lagoon and are potentially still hydraulically linked to the water of the lagoon.

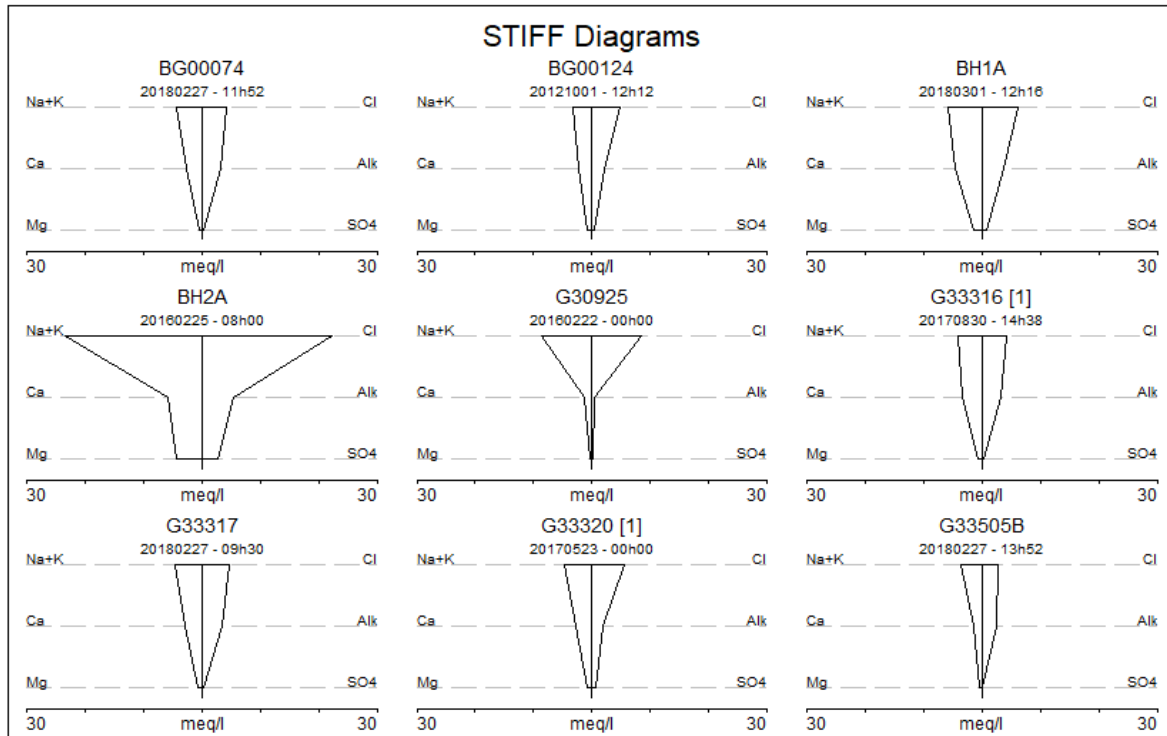


Figure 120: Stiff plots for representative geosites for Elandsfontein aquifer unit (generated with WISH; Lukas, 2012).

The data points on Piper diagramme for the Grootwater aquifer unit plots where one would expect the water quality of a coastal aquifer to lie (Figure 121). The data points form a single cluster showing a sodium-chloride type water.

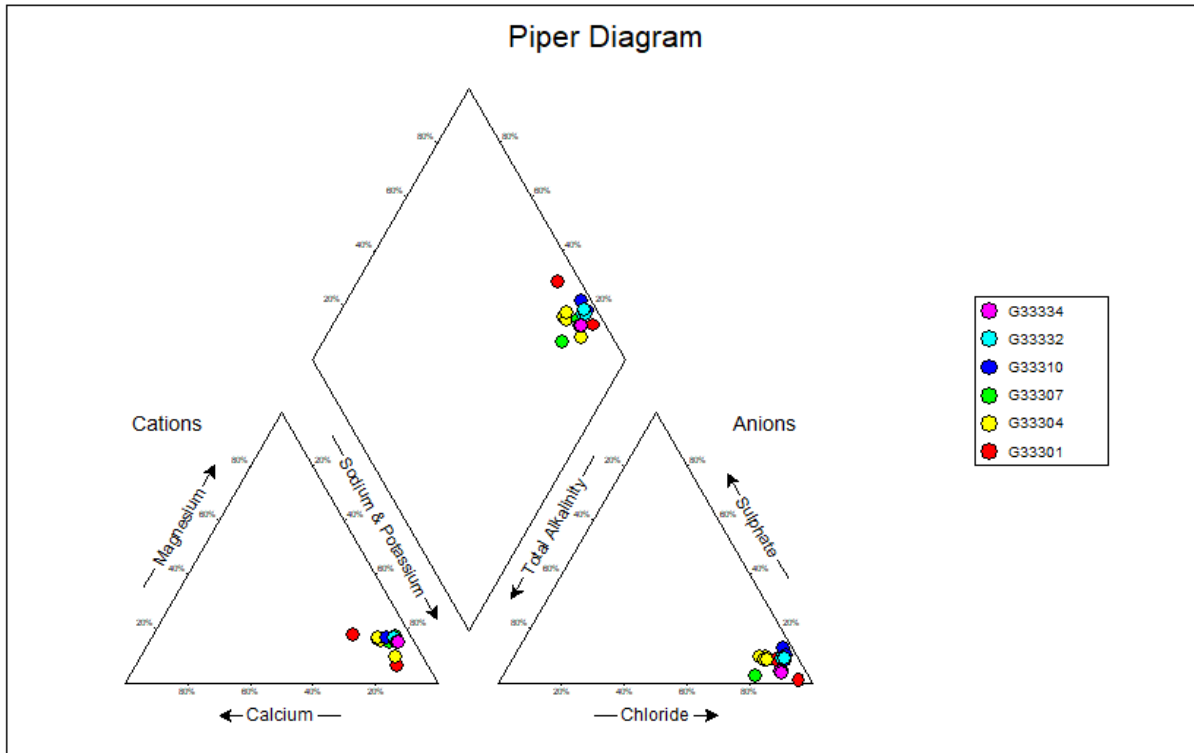


Figure 121: Piper diagramme for representative points in the Grootwater aquifer unit (generated with WISH; Lukas, 2012).

There is a bit more variation in the Stiff plots for the Grootwater aquifer unit (Figure 122). The water quality in this aquifer unit is good when considering its proximity to the coast, with EC measurements for most of the boreholes below 100mS/m. G33301, which is the furthest inland and some of the boreholes closest to the coast has EC values over 100mS/m. All the boreholes have a sodium-chloride type water, with magnesium featuring strongly in some cases. There are no significant calcrete deposits in the area that can potentially affect the water chemistry.

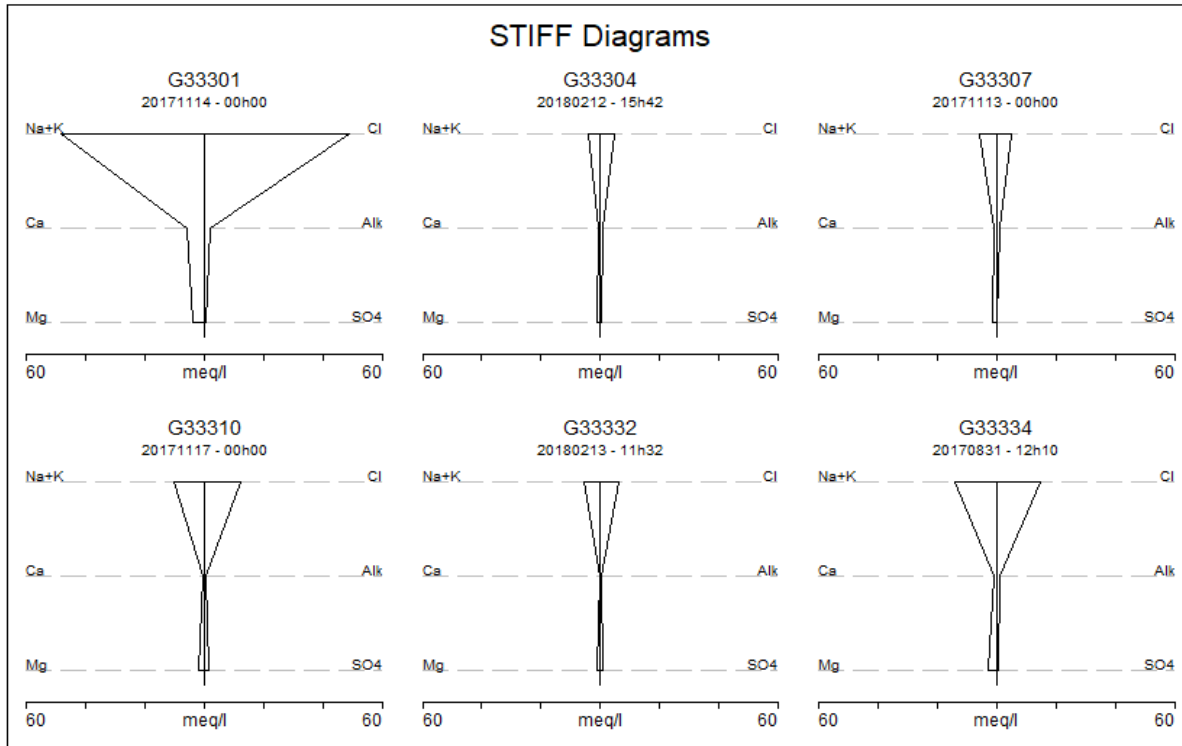


Figure 122: Stiff plots for representative boreholes in the Grootwater aquifer unit (generated with WISH; Lukas, 2012).

The water quality data was entered into the PhreeqC modeling programme and the programme was allowed to run its analysis (See Table 21). The outcome was analyzed for the most dominant ions. It is clear from the results that chloride (Cl^-) is the ion with the highest concentration in almost all of the sampling points. Chloride dominance, according to Freeze and Cherry (1979), is usually associated with deep groundwater flow systems in sedimentary basins, where the groundwater evolved past the stage where SO_4^{2-} is the dominant ion. This is likely to happen if the groundwater comes into contact with highly soluble chloride minerals like halite or sylvite, that occur in deep sedimentary basins as salt strata that was originally deposited during the evaporation of closed or restricted marine basins. The solubilities of other chloride minerals of sedimentary origin are very high, with the result that they dissolve rapidly in water. In the Langebaan Road area, the dominance of chloride cannot be explained by these processes, since most of the monitoring is done for the upper aquifer, where there were no opportunity for the evolution of groundwater through a long travelling time and the geology seems to indicate that bicarbonate (HCO_3^-) should be the dominant anion because of the abundance of calcrete in the area. The prominent chloride anion (Cl^-) of some of the boreholes in this case can probably be assigned to oceanic sources, since ocean spray carried inland by air streams can be deposited by rainfall (Noble, 1976). High levels of evaporation during the dry summer months may also influence the results.

Table 21: Results from PhreeqC modelling for the February 2008 sampling run for each of the monitoring points, with the major constituents in mol/ℓ, for the five constituents with the highest concentrations.

Borehole number	pH	Ionic strength	% error	Major constituents				
G32935 2008/02/12	8.010	1.594X10 ⁻²	2.96	Cl ⁻ (1.006X10 ⁻²)	Na ⁺ (8.765X10 ⁻³)	HCO ₃ ⁻ (2.186X10 ⁻³)	Ca ²⁺ (1.795X10 ⁻³)	
G33325 2008/02/15	7.838	9.053X10 ⁻³	-2.68	Na ⁺ (5.575X10 ⁻³)	Cl ⁻ (5.547X10 ⁻³)	HCO ₃ ⁻ (1.474X10 ⁻³)	Mg ²⁺ (5.745X10 ⁻⁴)	SO₄²⁻ (4.321X10⁻⁴)
G32926 2008/02/14	7.293	1.269X10 ⁻²	2.15	Cl ⁻ (8.445X10 ⁻³)	Na ⁺ (7.958X10 ⁻³)	HCO ₃ ⁻ (1.167X10 ⁻³)	Mg ²⁺ (9.481X10 ⁻⁴)	Ca²⁺ (5.021X10⁻⁴)
G46025 2008/02/12	8.194	6.613X10 ⁻³	-0.92	Cl ⁻ (2.857X10 ⁻³)	Na ⁺ (2.482X10 ⁻³)	HCO ₃ ⁻ (2.012X10 ⁻³)	Ca ²⁺ (1.050X10 ⁻³)	Mg²⁺ (2.361X10⁻⁴)
G46026 2008/02/12	7.884	7.665X10 ⁻³	-2.05	Cl ⁻ (3.170X10 ⁻³)	Na ⁺ (2.646X10 ⁻³)	HCO ₃ ⁻ (1.484X10 ⁻³)	Ca ²⁺ (1.122X10 ⁻³)	SO₄²⁻ (5.513X10⁻⁴)
G46028 2008/02/13	8.217	1.092X10 ⁻²	1.63	Cl ⁻ (4.974X10 ⁻³)	Na ⁺ (4.238X10 ⁻³)	HCO ₃ ⁻ (2.977X10 ⁻³)	Ca ²⁺ (1.719X10 ⁻³)	Mg²⁺ (4.420X10⁻⁴)
G46030 2008/02/13	8.247	7.066X10 ⁻³	-1.17	Cl ⁻ (3.041X10 ⁻³)	Na ⁺ (3.326X10 ⁻³)	HCO ₃ ⁻ (2.732X10 ⁻³)	Ca ²⁺ (9.068X10 ⁻⁴)	Mg²⁺ (2.534X10⁻⁴)
G46031 2008/02/13	8.264	9.885X10 ⁻³	0.38	Cl ⁻ (4.130X10 ⁻³)	Na ⁺ (3.320X10 ⁻³)	HCO ₃ ⁻ (3.003X10 ⁻³)	Ca ²⁺ (1.777X10 ⁻³)	Mg²⁺ (3.129X10⁻⁴)
G46032 2008/02/12	8.549	2.429X10 ⁻²	-1.58	Cl ⁻ (1.317X10 ⁻²)	Na ⁺ (9.950X10 ⁻³)	HCO ₃ ⁻ (4.139X10 ⁻³)	Ca ²⁺ (2.879X10 ⁻³)	Mg²⁺ (1.329X10⁻³)
G33327 2007/09/06	7.851	7.812X10 ⁻³	2.43	Cl ⁻ (3.934X10 ⁻³)	Na ⁺ (3.570X10 ⁻³)	HCO ₃ ⁻ (1.967X10 ⁻³)	Ca ²⁺ (1.087X10 ⁻³)	Mg²⁺ (3.110X10⁻⁴)
G32937 2008/02/14	8.057	7.721X10 ⁻³	-1.93	Cl ⁻ (3.911X10 ⁻³)	Na ⁺ (3.15X10 ⁻³)	HCO ₃ ⁻ (2.059X10 ⁻³)	Ca ²⁺ (1.143X10 ⁻³)	Mg²⁺ (2.364X10⁻⁴)
G33324 2008/02/14	8.151	5.193X10 ⁻²	-1.34	Cl ⁻ (3.781X10 ⁻²)	Na ⁺ (3.296X10 ⁻²)	HCO ₃ ⁻ (5.077X10 ⁻³)	Ca ²⁺ (3.072X10 ⁻³)	Mg²⁺ (2.477X10⁻³)
G33326 2008/02/15	8.110	1.025X10 ⁻²	-1.26	Cl ⁻ (6.401X10 ⁻³)	Na ⁺ (5.770X10 ⁻³)	HCO ₃ ⁻ (2.159X10 ⁻³)	Ca ²⁺ (1.079X10 ⁻³)	Mg²⁺ (3.063X10⁻⁴)
G46055 2008/02/14	8.319	8.388X10 ⁻³	-1.09	Cl ⁻ (4.148X10 ⁻³)	Na ⁺ (4.027X10 ⁻³)	HCO ₃ ⁻ (2.746X10 ⁻³)	Ca ²⁺ (1.022X10 ⁻³)	Mg²⁺ (3.235X10⁻⁴)

Table continued

Borehole number	pH	Ionic strength	% error	Major constituents				
G46056 2008/02/15	8.252	8.128X10 ⁻³	-1.06	Na ⁺ (4.873X10 ⁻³)	Cl ⁻ (4.752X10 ⁻³)	HCO ₃ ⁻ (2.202X10 ⁻³)	Ca ²⁺ (8.294X10 ⁻⁴)	Mg ²⁺ (1.808X10 ⁻³)
G46058 2008/02/15	8.247	3.553X10 ⁻²	-1.58	Cl ⁻ (2.302X10 ⁻²)	Na ⁺ (1.687X10 ⁻²)	HCO ₃ ⁻ (3.934X10 ⁻³)	Ca ²⁺ (3.397X10 ⁻³)	Mg ²⁺ (2.212X10 ⁻³)
G46059 2008/02/14	8.054	8.491X10 ⁻³	-1.27	Cl ⁻ (4.353X10 ⁻³)	Na ⁺ (3.650X10 ⁻³)	HCO ₃ ⁻ (1.958X10 ⁻³)	Ca ²⁺ (1,217X10 ⁻³)	Mg ²⁺ (2.815X10 ⁻⁴)
G46060 2008/02/14	8.227	1.255X10 ⁻²	-2.44	Cl ⁻ (6.641X10 ⁻³)	Na ⁺ (5.826X10 ⁻³)	HCO ₃ ⁻ (3.026X10 ⁻³)	Ca ²⁺ (1.537X10 ⁻³)	Mg ²⁺ (4.564X10 ⁻⁴)
G46062 2008/02/15	7.536	3.748X10 ⁻²	0.11	Cl ⁻ (2.950X10 ⁻²)	Na ⁺ (2.163X10 ⁻²)	Mg ²⁺ (3.385X10 ⁻³)	Ca ²⁺ (1.542X10 ⁻³)	HCO ₃ ⁻ (7.957X10 ⁻⁴)
G46063 2008/02/12	8.175	5.003X10 ⁻²	0.95	Cl ⁻ (3.443X10 ⁻²)	Na ⁺ (3.322X10 ⁻²)	HCO ₃ ⁻ (5.081X10 ⁻³)	Mg ²⁺ (3.147X10 ⁻³)	Ca ²⁺ (1.905X10 ⁻³)
GK10 2008/02/15	8.232	1.032X10 ⁻²	1.15	Cl ⁻ (4.063X10 ⁻³)	Na ⁺ (3.505X10 ⁻³)	HCO ₃ ⁻ (3.076X10 ⁻³)	Ca ²⁺ (1.673X10 ⁻³)	Mg ²⁺ (4.813X10 ⁻⁴)
G46090 2008/02/13	8.127	9.724X10 ⁻²	1.66	Cl ⁻ (7.458X10 ⁻²)	Na ⁺ (6.832X10 ⁻²)	Mg ²⁺ (5.371X10 ⁻³)	HCO ₃ ⁻ (4.872X10 ⁻³)	Ca ²⁺ (3.752X10 ⁻³)
G46092 2008/02/15	8.027	4.936X10 ⁻²	0.10	Cl ⁻ (4.025X10 ⁻²)	Na ⁺ (3.573X10 ⁻²)	Mg ²⁺ (2.597X10 ⁻³)	HCO ₃ ⁻ (2.589X10 ⁻³)	Ca ²⁺ (1.559X10 ⁻³)
G46097 2008/02/15	7.981	7.662X10 ⁻³	-4.00	Cl ⁻ (3.995X10 ⁻³)	Na ⁺ (3.231X10 ⁻³)	HCO ₃ ⁻ (1.495X10 ⁻³)	Ca ²⁺ (9.775X10 ⁻⁴)	SO ₄ ²⁻ (3.655X10 ⁻⁴)
G46095 2008/02/13	8.142	9.309X10 ⁻³	0.37	Cl ⁻ (4.698X10 ⁻³)	Na ⁺ (4.066X10 ⁻³)	HCO ₃ ⁻ (2.588X10 ⁻³)	Ca ²⁺ (1.356X10 ⁻³)	Mg ²⁺ (3.217X10 ⁻⁴)
G46101 2007/11/13	8.091	2.122X10 ⁻¹	-0.64	Cl ⁻ (1.687X10 ⁻¹)	Na ⁺ (1.39X10 ⁻¹)	Mg ²⁺ (1.519X10 ⁻²)	HCO ₃ ⁻ (7.390X10 ⁻³)	Ca ²⁺ (6.604X10 ⁻³)
G46103 2008/02/15	8.030	4.035X10 ⁻²	1.89	Cl ⁻ (2.721X10 ⁻²)	Na ⁺ (2.530X10 ⁻²)	HCO ₃ ⁻ (5.969X10 ⁻³)	Mg ²⁺ (2.668X10 ⁻³)	Ca ²⁺ (2.213X10 ⁻³)
G46104 2008/02/14	7.953	6.291X10⁻²	-0.15	Cl⁻ (4.754X10⁻²)	Na⁺ (4.269X10⁻²)	Mg²⁺ (3.961X10⁻³)	HCO₃⁻ (3.830X10⁻³)	Ca²⁺ (1.977X10⁻³)

Table continued								
Borehole number	pH	Ionic strength	% error	Major constituents				
G46106 2008/02/13	8.186	1.139X10 ⁻¹	0.42	Cl ⁻ (9.013X10 ⁻²)	Na ⁺ (7.640X10 ⁻²)	Mg ²⁺ (7.064X10 ⁻³)	HCO ₃ ⁻ (5.327X10 ⁻³)	Ca ²⁺ (4.601X10 ⁻³)
G46112 2008/02/14	8.345	5.910X10 ⁻²	-0.02	Na ⁺ (4.269X10 ⁻²)	Cl ⁻ (4.029X10 ⁻²)	HCO ₃ ⁻ (6.919X10 ⁻³)	Mg ²⁺ (2.494X10 ⁻³)	SO ₄ ²⁻ (2.086X10 ⁻³)
BG00001 2008/02/13	7.974	2.395X10 ⁻¹	-1.63	Cl ⁻ (1.876X10 ⁻¹)	Na ⁺ (1.285X10 ⁻¹)	Mg ²⁺ (1.918X10 ⁻²)	Ca ²⁺ (1.386X10 ⁻²)	SO ₄ ²⁻ (5.359X10 ⁻³)
G45632 2008/02/12	7.943	6.848X10 ⁻³	3.05	Cl ⁻ (2.903X10 ⁻³)	Na ⁺ (2.673X10 ⁻³)	HCO ₃ ⁻ (1.971X10 ⁻³)	Ca ²⁺ (1.154X10 ⁻³)	Mg ²⁺ (2.208X10 ⁻⁴)
BG00066 2008/02/13	8.110	1.025X10 ⁻¹	1.83	Cl ⁻ (7.957X10 ⁻²)	Na ⁺ (6.898X10 ⁻²)	Mg ²⁺ (6.573X10 ⁻³)	Ca ²⁺ (4.162X10 ⁻³)	HCO ₃ ⁻ (3.732X10 ⁻³)
BG00062 2008/02/13	7.994	8.963X10 ⁻²	-0.60	Cl ⁻ (6.948X10 ⁻²)	Na ⁺ (5.356X10 ⁻²)	Mg ²⁺ (6.471X10 ⁻³)	Ca ²⁺ (4.573X10 ⁻³)	HCO ₃ ⁻ (4.380X10 ⁻³)
BG00063 2007/09/06	8.176	1.130X10 ⁻¹	-0.71	Cl ⁻ (9.023X10 ⁻²)	Na ⁺ (6.388X10 ⁻²)	Mg ²⁺ (8.782X10 ⁻³)	Ca ²⁺ (6.342X10 ⁻³)	HCO ₃ ⁻ (2.563X10 ⁻³)

Sodium is the second most dominant ion (the most dominant cation) in the system in most of the cases, and in some cases the concentrations of sodium is higher than that of the chloride. The dominant sodium (Na⁺) component may be linked to elevated salinity that can be correlated to shale formations in South Africa, but it is possible that other factors contribute to the high salinity (Noble, 1976). Figure 123 shows the Stiff plots for representative data points to give an indication of the water type of each aquifer unit and to show how it correlates with the findings of the phreeqC analysis. The blue polygon represents the TMG aquifers. The orange polygon indicates the Adamboerskraal aquifer unit boreholes with the pink polygon representing the Langebaan Road aquifer unit. The green and yellow polygons represent the Elandsfontein and Grootwater aquifer units respectively. G46024 is an upper aquifer layer borehole in the area considered to be one of the local natural recharge sites for the Langebaan Road aquifer unit, and potentially also

for the Elandsfontein aquifer unit. G32926 is a lower aquifer layer borehole on the upper edge of the Langebaan Road palaeochannel. G46105 is a basement aquifer borehole at the wellfield. G33323 is one of the boreholes closest to the Berg River, while G46106 is one of the boreholes closest to Saldanha Bay. G33255 and G33249 is in two different palaeochannels forming the Adamboerskraal aquifer unit. Borehole 37/1 is on top of the mountains and 3218CB/CA1 is a spring at the foot of the mountain just outside Aurora. BG00124 is a production borehole on the farm Theefontein on the one end of the Elandsfontein aquifer unit, G33317 is a monitoring borehole in the middle of the Elandsfontein aquifer unit and BH1A is at Geelbek, next to the Langebaan Lagoon. G33301 and G33332 are boreholes on the Grootwater aquifer unit and are representative of different palaeochannel systems. BG00071 is just north of Darling and was drilled into the Colenso Fault System, while KN (ZQMHPF1) is a dug well on the farm Koperfontein just south of the town of Hopefield.

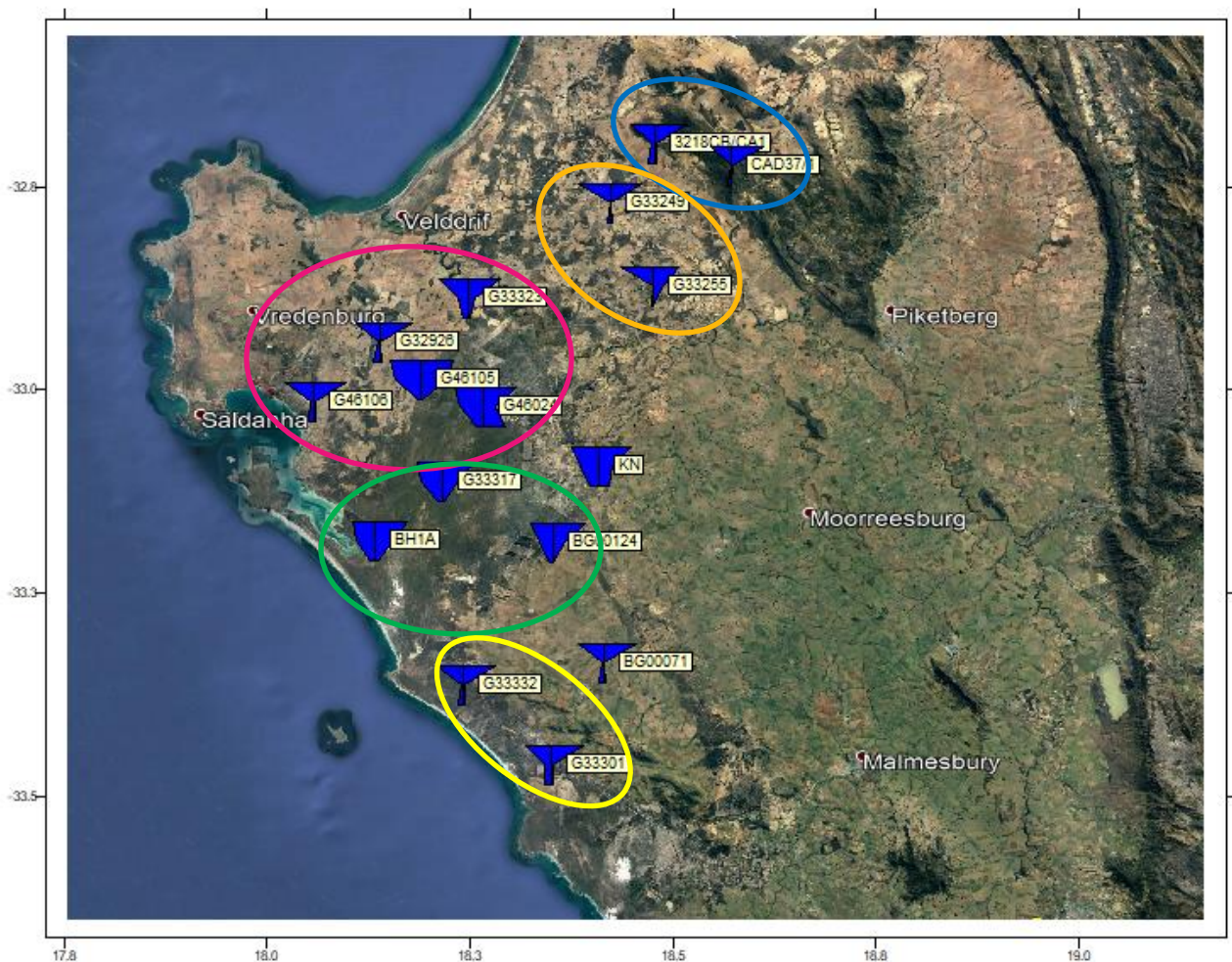


Figure 123: Stiff plots of the different aquifer units to give an indication of water quality type for each (generated with WISH; Lukas, 2012).

Gypsum or calcrete may be the source of the higher components of calcium and sulphate in some cases. The effects of the decomposition of peat may also contribute to the higher calcium and

sulphate concentrations (Noble, 1976). In the results from the modelling, we find that bicarbonate, rather than sulphate is the second most dominant anion in the system, and in only a few cases do sulphate feature amongst the top five ions. This may be because calccrete, a source of bicarbonate, is more abundant than gypsum in the study area.

Calcium (Ca^{2+}) is in most cases the second most dominant cation, which is correlates with the geology of the area. The high concentrations of magnesium (Mg^{2+}) in some cases were surprising, especially where its concentrations were higher than that of the calcium. The dissolution of dolomite and epsomite may cause higher concentrations in magnesium in the groundwater, with dolomite also contributing to an increase in calcium (Freeze and Cherry, 1979). The borehole logs (see Table 3, Appendix) of a number of the sampling points that have higher magnesium concentrations than calcium concentrations show that it had been drilled through granite, which might contribute to the higher magnesium concentrations (Smart, 2009).

The conductivity of the major part of the study area is less than 100mS/m, with the best quality of water occurring in the central part. The water quality deteriorates towards the Berg River in the north and Saldanha Bay in the west (Timmerman, 1985a). The results from this study seem to agree with that done by Timmerman in 1985, where a major part of the study area has an EC below 100mS/m.

4.6 Correlation between surface water and groundwater levels

Analyzing the water levels of the boreholes raised the question about the link between the water levels in the Berg River and the Lower Berg River aquifer system. Figure 124 shows the data record for flow gauge G1H013 at Drieheuvels from 1964 to 2018 (the red indicates where data gaps were filled). It is clear from this record that 2007 was the year with the highest flow with the highest peak measured on 2007/06/07 at 7:48 with a reading of 6.560m. The effects of the recent drought can also be seen from around 2015, with no peaks for 2018 and no flow for the last couple of weeks on the data record. This was probably the first time in the history of the river that flow over the weir ceased.

Region: » All Stations «
Meas. values

Station:
Sensor:

Drieheuvels
Drieheuvels/G1H013

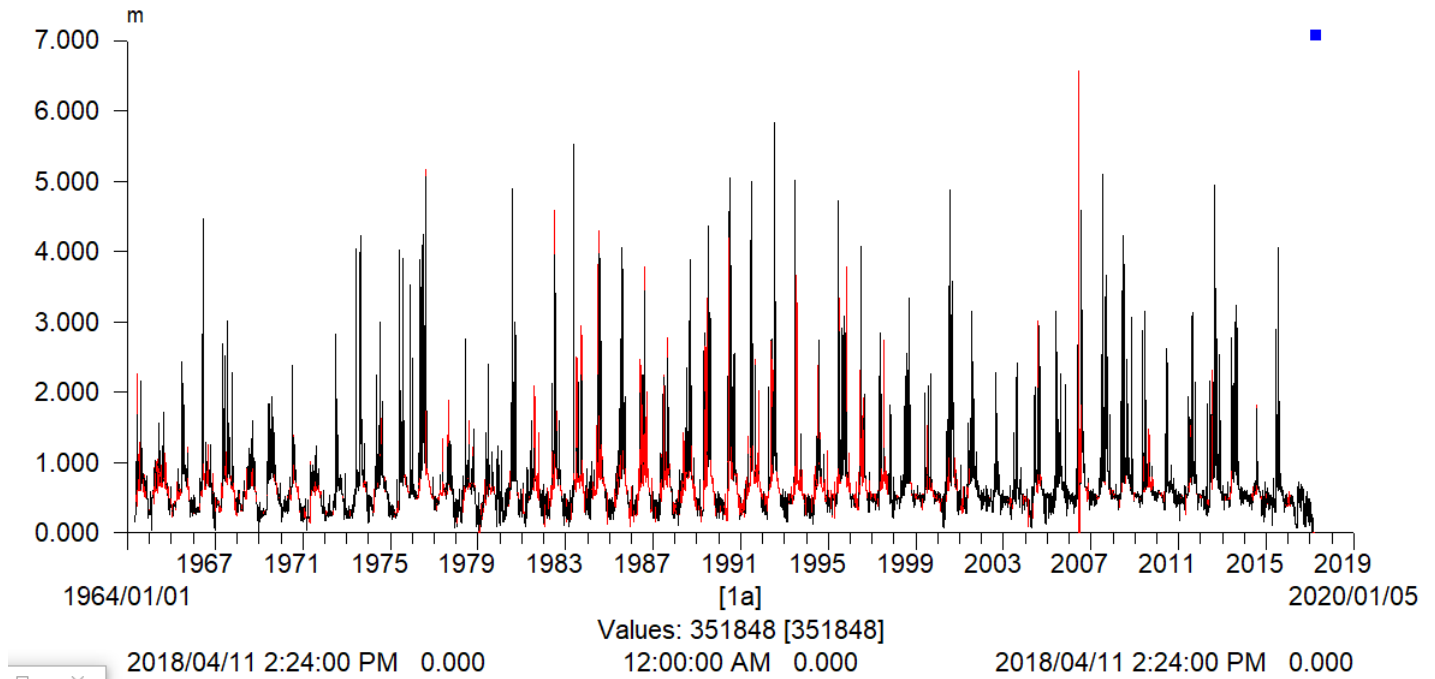


Figure 124: Time series graph of streamflow generated in Hydras3 for gauge G1H013 upstream of G33323.

Figure 125 shows that there is a high correlation of the waterflow over the weir at Drieheuvels with water levels measured in borehole G33323. There is a time lag of about a month between the highest peaks in streamflow compared to the groundwater level peaks in the borehole which would account for the time it takes for the water to flow from the weir and infiltrate into the aquifer system to impact the water levels. The highest peak in groundwater levels were also measured in 2007, with another high peak in 2013. This agrees with the peaks in streamflow. The very low flow levels measured in 2018 correlates with the water levels in the borehole and corroborates the findings of Andries (2019) that the river did not contribute to recharge at the time.

† G33323/Cloetes kraal/Waterlevels@G33323
 * G33323/Cloetes kraal/Waterlevels@G33323
 ▲ Drieheuvels/Drieheuvels/G1H013

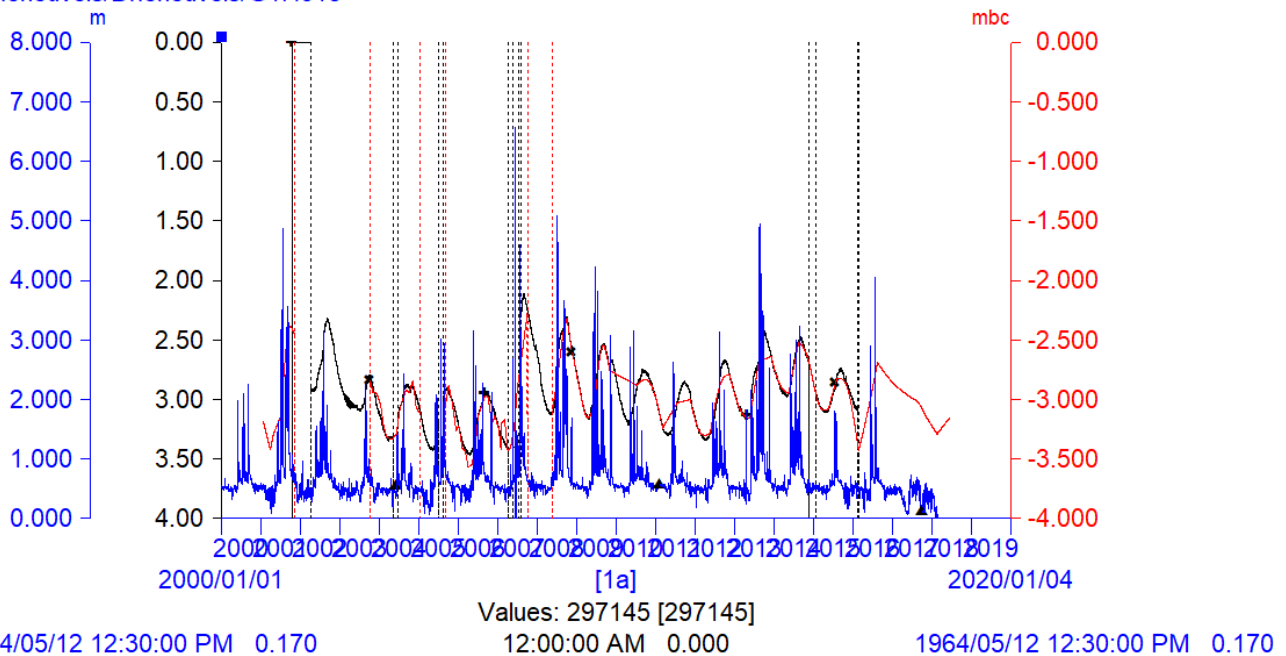


Figure 125: Time series graph generated in Hydras3 showing the comparison of water levels in borehole G33323 and flow gauge G1H013.

Further analysis of the correlation between stream flow and groundwater levels may be necessary in order to have a better idea of the contribution of the river to recharge and the aquifer to baseflow in the river during low flow periods.

4.7 Discharge

Discharge rates from an aquifer depends on the hydraulic head in the aquifer, which is in turn dependent on the recharge to the aquifer (Smalls, et al., 2019). Discharge from the aquifer system will take place towards a number of surface water bodies in the study area. This includes, but is not limited to the

- Langebaan Lagoon;
- Saldanha Bay;
- Berg River and non-perennial rivers in area (base flow); and
- Pans, wetlands and springs.

The volume of discharge has not been quantified yet, and the only estimates is the ones done by Woodford (2004). Isotope analysis by Andries (2019) has confirmed that the Elandsfontein aquifer unit is in hydraulic connection with the Langebaan Lagoon at Geelbek. The possibility exists that the interaction between the Elandsfontein aquifer unit and the Langebaan Lagoon could be a subterranean estuary. Information from game rangers in the West Coast National Park give further credence to the idea of a subterranean estuary since the dug wells along the coast show fluctuating water levels and changes in the water quality in time with the tides.

The isotope analysis also shows a link with the Berg River, with the aquifer system contributing to the flow in the river as baseflow (Andries, 2019). The discharge to the Berg River will depend on the water level in the aquifer system.

4.8 Groundwater dependent ecosystems

A proper assessment of groundwater dependent ecosystems has not been done for the area. The WRC study on aquifer dependent ecosystems for Geelbek (Colvin, et al., 2007) was the only study was done on groundwater dependent ecosystems in the area. shows the Numerous wetlands, pans and springs occur in the area (**Error! Reference source not found.** for the northern part of the study area and Figure 127 for the southern part). They are easier to find in unimpacted areas as it was not disturbed by agricultural activities. It is possible that some of the wetlands or springs may be the remnants of oxbow lakes that was formed when the meandering river changes its course, especially on the vicinity of Langebaan Road. The riparian zones of the non-perennial rivers and the perennial rivers, especially the Berg River, may also be included in this category, as groundwater contributes to the systems in the form of baseflow.

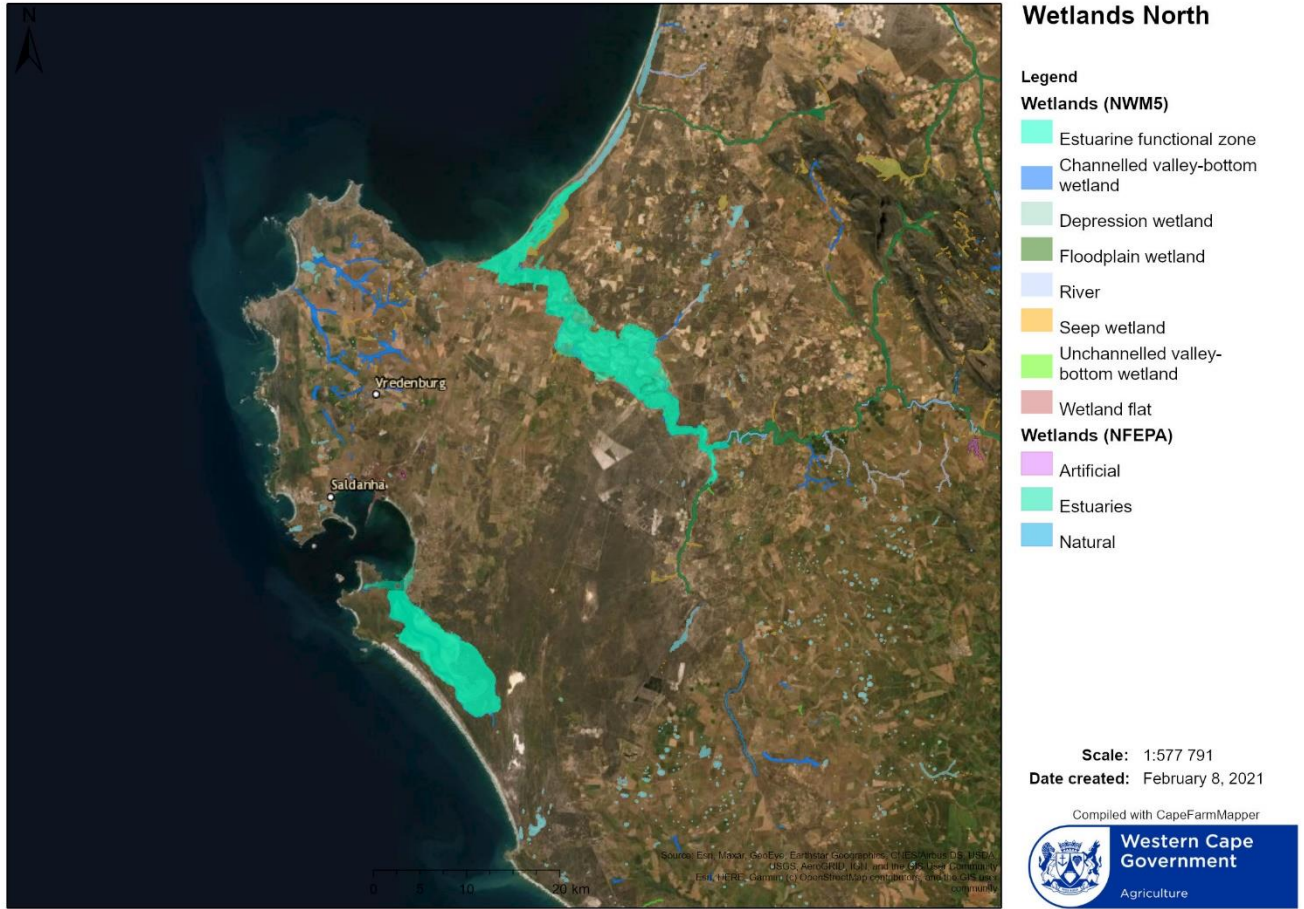


Figure 126: Satellite image showing some of the wetlands, riparian zones and pans in the northern part of the study area (WC Dept.A, 2021).

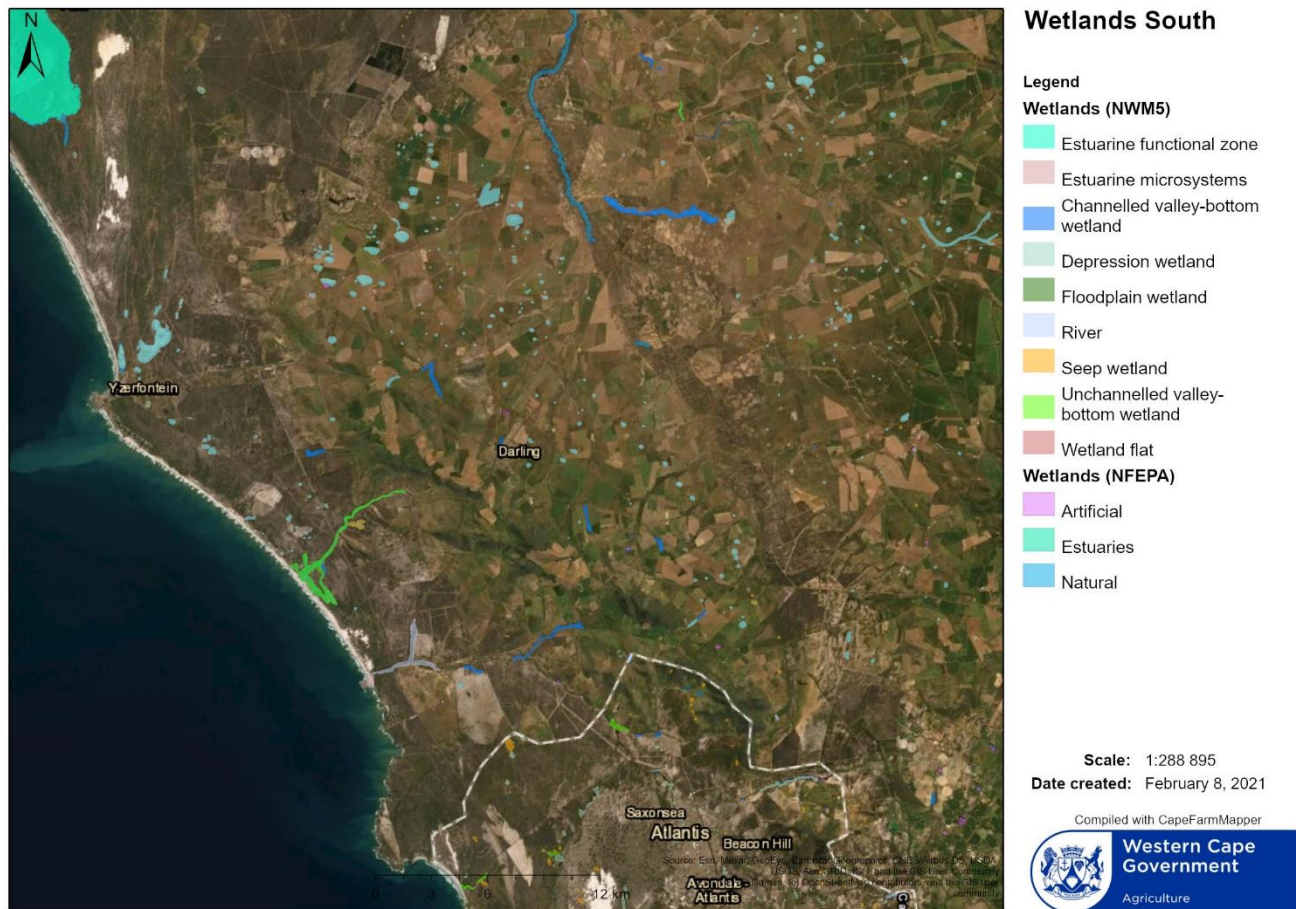


Figure 127: Satellite image showing some of the wetlands, riparian zones and pans in the southern part of the study area (WC Dept.A, 2021).

4.9 Summary

A large volume of data and information is available for the study area, with only a small portion of it presented above. It becomes clear from the analysis of the information available that the aquifer system is complex and that it still holds secrets to be unraveled.

These secrets include the recharge areas and volumes of recharge. The recent work by Smith (2019), Andries (2019), Spannenberg (2015), Ebrahim (2015) and others contributed to the understanding of the recharge to the system, but some questions remain. This includes the apparent contradicting findings of Smith (2016) and Andries (2019) about the source of the recharge.

Rainfall in the area is important, but highly unpredictable and will potentially be negatively impacted by climate change. Better analysis of the correlations between rainfall and groundwater levels may add to an improved understanding of the recharge in the area. It may be necessary to analyze the data of rainfall stations outside the study area to get an idea of all the potential recharge to the aquifer system. There is a high correlation between rainfall and water levels for

boreholes in the upper, unconfined layers. This correlation is limited or lacking in the semi-confined and confined layers.

The groundwater level graphs tell a story that is there for all to read if they are willing to take the time to unravel it. Part of the story is that there seems to be a connection between the Adamboerskraal, Langebaan Road and Elandsfontein aquifer units, but the exact extent of this connection is still uncertain. They do give an indication of the impacts of natural and artificial recharge (MAR), and abstraction at the wellfield and elsewhere. The CDM plots and other statistical analysis helps to explain the water levels in greater detail, and further statistical analysis would help to unlock more information from the available data records. It would be necessary to take some more time to really find all the hidden meanings behind the story. This would include investigating the level and extent of the impact, the reasons why this impact is sometimes seen in both upper and lower aquifer layers, the time lags between events, and many others.

The water quality shows a clear link between the geology of the area and its setting close to the sea. Most of the area has a surprisingly good water quality for an aquifer system this close to the sea, and it is important to do everything possible to protect this water quality that is so important for the environment and human needs in this area. The unconfined aquifer layers at times have water quality comparable to that of the lower semi-confined to confined layers. These are, however, more vulnerable to the impacts of human activities. The calcrete layers, even if not extensive, may contribute some protection to the quality of the upper aquifer layers, and its removal may create problems such as higher evaporation and changes in quality.

The link between surface water bodies and groundwater dependent ecosystems in the study area is not clearly understood yet. It should receive more attention, as it is important to ensure that activities such as abstraction does not damage the ecosystem. There seem to be a high correlation between streamflow and groundwater levels along the Berg River, but the extent of the interaction is not well documented. The contribution of the non-perennial rivers to recharge has not been investigated, nor the contribution of the aquifers to baseflow in these rivers and the Berg River.

All the different factors need to be considered in the development of a conceptual model. What was presented in this chapter provided some puzzle pieces to form a more complete picture of the groundwater system and its links to the ecosystem it serves. It will also contribute to a more effective, sustainable management of the resource. These results will be used in formulating the conceptual model that will be presented in words and pictures in Chapter 5.

Chapter 5: Conceptual Model



G33967 on the Farm Jakkalsfontein (13 February 2018)

The request to investigate the importance of a number of monitoring points in the West Coast (Vermaak and De Haast, 2009) sparked an interest in the region that has grown into a fascination and some may even say an obsession. At first it looks like a simple system, consisting of the sedimentary deposits in a number of palaeochannels. It thus seems fairly simple to delineate the aquifer units, determine flow patterns and calculate volumes available. Using the accepted geohydrological principle that a topographical high equal a groundwater divide, you basically have an explanation of the groundwater system. This made up the conceptual model that has been used for the West Coast Aquifer System since the Timmermans penned their ground-breaking work in a series of reports in 1985 (Timmerman, K.M.G., 1985; Timmerman, 1985a, 1985b, 1985c, 1985d) followed by the D.Sc. thesis of L.R.A. Timmerman (1988). This conceptual model has formed the basis of most scientific work and models since then.

When looking at the system closely, you find that it is not just a straightforward sedimentary system in a series of palaeochannels. There is a level of complexity that would normally be associated with sedimentary deposits in a river system. Timmerman had picked up on the layers and built it into his conceptual model in a greatly simplified layered system. It was the work of Edgar Stettler that began questioning the continuity of the clay layers at the Langebaan Road Aquifer Unit, the observations of farmers in the area with regards to water levels in their dug wells and the work of Alan Woodford for the West Coast District Municipality in connection with the operation of the wellfield that began to throw some doubt on the conceptual model built by Timmerman. Most scientist, however, continued working with the Timmerman model.

Water level time series graphs for the monitoring points in the West Coast were plotted in the investigating of the monitoring points in question, and an interesting pattern emerged. Water levels in the Elandsfontein Aquifer Unit were dropping from around July 2000. There was no large-scale abstraction in the area; it was a pristine nature reserve. Abstraction at the Langebaan Road wellfield began in December 1999, but according to the Timmerman model, it should not impact the Elandsfontein Aquifer Unit. Yet it could be the only rational explanation. The conclusion was that there must be a link between the two aquifer units. Vindication came a year or two later when reading some of the reports by Woodford and Fortuin (2003) where he indicated that the drawdown cone from the wellfield affected the water levels in borehole G33320, which is in the Elandsfontein Aquifer Unit. He also plotted an inferred shale-granite contact on his geological maps, that could act as a link between the two aquifer units, using the contact zone as a preferential pathway.

A quest thus began in an attempt to find the answers to the West Coast Aquifer System and the way it functions. It has led to numerous discussions with eminent geologists, searching of archives, reading of reports, plotting of monitoring data on time series graphs, analyzing the data, running geochemical models, and finally became the basis for this study. Some of these findings were discussed in Chapter 4. This chapter will look at the historical understanding of the area, describing the conceptual model built by L.R.A. Timmerman, K.M.G. Timmerman, and Vandoolaeghe, and the work that was done afterwards. It will then propose a regional model, based on current understanding and a lot of conjecture as a result of limited information – maybe leaving some thoughts for others to investigate. Finally, it will unpack the new conceptual model, explaining how it differs from that of Timmerman (1988), using monitoring data and the most recent work done by the Council of Geoscience (Roberts and Siegfried, 2014) and a number of scientists.

The chapter will begin with a regional picture, which is still very unclear, and thus only presents possibilities of what may be, and provide some ideas for further research. It will then move to the local situation, which is better known and can be substantiated with monitoring data, borehole logs and other information.

5.1 Regional Picture

Coastal aquifers should not be seen as units on their own. They need to be seen in the context of the wider regional setting and the possible interactions with other aquifer types. The West Coast Aquifer System should be seen in the context of the basement aquifers – Malmesbury shale and Cape Granite Suite – that is underlying the system and the TMG aquifers that is adjacent to the area. These aquifers may be feeding into the coastal aquifer systems through faults and other structures, as well as on a more local scale by leaking into the coastal aquifers.

The geology of the area is one of the main factors in the geohydrological characteristics of the West Coast Aquifer System. It is important to look at the regional geology and its possible influence on the coastal aquifers in the Lower Berg River Valley. The geology can almost be divided into macro scale features – i.e., the fault systems and palaeochannels – and the almost microscale features that include the different layers that make up the various layers in the aquifer units with their unique characteristics. These characteristics include grain size and shape, pores spaces, presence of peat, etc. It is almost a requirement to have some sort of understanding of sedimentology and geomorphology to understand the depositional environments of the different layers.

5.1.1 Palaeochannels

The palaeochannels (also known as buried valleys) are the ancient flow paths of rivers. In the case of the Lower Berg River Aquifer System, the system is made up of the palaeochannels of the Berg, Groen, Kuilders and other smaller rivers. Figure 128 shows the approximate extent of the Cenozoic deposits that are used to delineate the four aquifer units that make up the Lower Berg River Aquifer System. The Grootwater Unit is to the south along the coast with the Atlantic Ocean. It is bounded by the Modder River to the south, the Darling Pluton on the east and was assumed to end along the Yzerfontein – Darling road on the north. According to the work done by Timmerman (1985a) the Grootwater Aquifer Unit consist of three palaeochannels that run from the Darling pluton towards the coast. It would roughly correspond to the Kransduinen River, Dwars River South and Dwars River North.

The area north of the Grootwater Unit was not properly investigated as a result of the extensive calcrete layers in the area and the problems it caused during drilling (Bertram, 2015). Some of the problems was that the drilling mud disappeared into cavities caused by the calcrete, but drill bits getting stuck was another. This could also be seen in the records for borehole G31345 (unpublished drilling records) that was drilled along the R27, and eventually abandoned because the drill bit kept getting stuck.

The Elandsfontein Aquifer Unit (Timmerman, 1985b, Smith, 1982) was found to consist mainly of the palaeochannel of the Groen River that begins in the vicinity of the Farm Rietfontein between the Darling Pluton north of Darling and the Groen River. The palaeochannel then flows in a northwesterly direction and turns into a southwesterly direction on the farm Elandsfontein. It discharges into the Langebaan Lagoon at Geelbek. It seems to be connected with the Langebaan

Road Unit by an area where the basement topography dips (Roberts and Siegfried, 2012), most probably along the inferred shale-granite contact running northwards from the Colenso Fault System (Woodford and Fortuin, 2003).

The Adamboerskraal Unit begins south of the Piketberg Mountains which is formed, according to the work by Karin Timmerman (1985), by three palaeochannels – the Berg River, the Kuilders River and the Papkuils River. The main channel is that of the Berg River and Karin Timmerman (1985) postulates that this channel connects with the Langebaan Road Aquifer Unit underneath the Berg River in its current position. The existence of the Berg River palaeochannel and the connection of the two aquifer units underneath the Berg River was confirmed by work done by the Council of Geoscience (Roberts and Siegfried, 2014; Cole, 2012).

The fourth aquifer unit, known as the Langebaan Road Unit, is also the one that had been studied most. It runs from the Berg River towards Saldanha Bay where it discharges to the bay. The basement of this aquifer unit is formed by the palaeochannel of the Berg River (Timmerman, 1985b; Smith, 1982).

The Lower Berg Aquifer System are, however, not limited to the palaeochannels, as the upper layers are more continuous, thereby creating a greater connectivity between the different unit. The different layers in these aquifer units will be discussed later when the local situation is described.

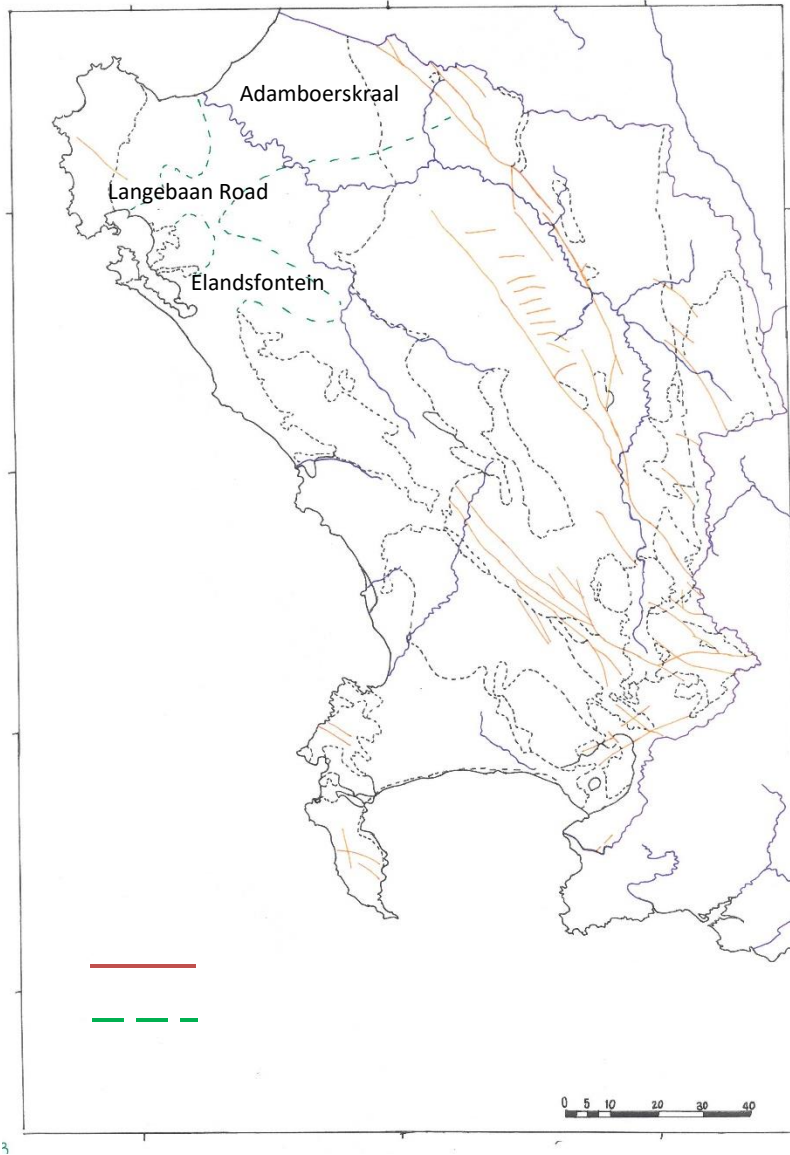


Figure 128: Map of the Berg catchment area showing the possible extent of the West Coast Aquifer System in broken green line.

5.1.2 Fault Systems

One of the dominant geological features in the area is the Colenso Fault System (otherwise known as the Saldanha-Franschhoek Fault Zone or the Vredenburg-Stellenbosch Fault Zone). It has its origins in the Franschhoek valley and disappears under the cenozoic deposits somewhere between Klapmuts and Kalbaskraal, showing itself briefly in the Franschhoek area, on the farm Wintervogel, on the Farm Colenso just north of Darling, and then reappearing between Saldanha and Vredenburg, before going into the sea (Vermaak, et al. 2019). Efforts to pinpoint the exact location of the Fault System has met with varying levels of success.

The 3319 Worcester 1:250 000 geological map (Council of Geoscience, 1997), shows a number of fault lines that have their origin in the Franschhoek valley (See Figure 129, which was derived from the original map). These fault lines form as it were a fan as it leaves the valley, but it cannot be traced further as a result of the thick sands. The possibility exists that there are a number of additional fault lines going in a northwesterly direction towards the Lower Berg River Valley (See Figure 49), thereby intersecting the Lower Berg River Aquifer System. At least two additional fault lines are possibly occurring on either side of the Colenso Fault. The fault lines will potentially have crushed zones that could act as preferential pathways for the flow of groundwater. This would correlate with the high yielding boreholes in the Dassenberg area of Atlantis, as well as the area around Abbotsdale (Cherry, 2016). R. Scheepers has cited the possibility of a fault line running along the Langebaan Lagoon towards Saldanha Bay (Roberts and Siegfried, 2014), which seem to confirm the conclusion reached by Cherry (2016) about the fault line to the west of the Colenso Fault. A second fault line to the east of the Colenso Fault may coincide with the Groen River and the mouth of the Berg River. R. Scheepers had also indicated the possible existence of a fault line that may lie beneath the Langebaan Road – Adamboerskraal palaeochannel. The Colenso Fault System and recent groundwater investigations has been discussed in Chapter 3. The results from the case studies discussed raised the idea that the Colenso Fault System can potentially act as a preferential pathway of high-quality water along its length from the recharge area in Franschhoek or Stellenbosch. This creates the possibility that these fault lines can contribute to the recharge of the West Coast Aquifer System. It is not possible to establish this as a fact, due to the paucity of data. The variability of the lithological composition of the country rock, deformation and granite intrusions make it difficult to determine a specific transmissivity for the Colenso Fault System. It will be necessary to do more groundwater exploration in the area.

The fault lines may have played a role in the direction that the Berg River and other rivers in the area flowed as it provides a conduit for preferential flow. The fault lines may thus have contributed to the formation of the palaeochannels. It would seem that the fault lines are basically strike-slip fault lines if one considers the displacement in the mountains at Franschhoek and at the Saint Helena Bay coast. Some vertical displacement may also have occurred. The movement in the faults may have also contributed to the capture of smaller rivers, like the Groen, and the Salt Rivers. This would have changed their direction towards the new flow path of the Berg River, leaving palaeochannels behind. There is a need to investigate the Colenso Fault System and its role on the groundwater systems in the Berg River catchment area further to know whether what is presented above is what is happening in reality.

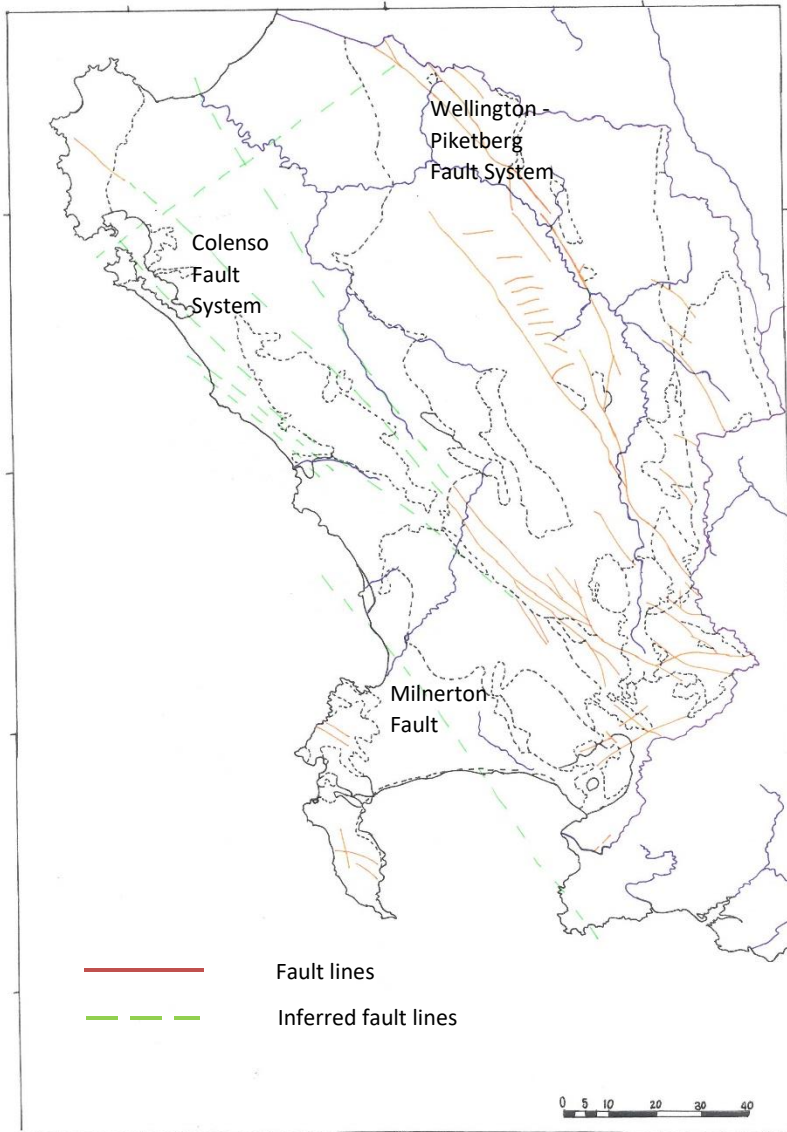


Figure 129: Map of the Berg catchment area with possible fault lines in broken green lines.

5.2 Local situation

There is a level of complexity in the West Coast Aquifer System that can be deceiving. In the end, it is just one unit made up of different layers of sediments that was deposited in palaeochannels in different environments. The whole system is driven by the geology, the depositional environments and the characteristics of the sediments. These characteristics have not been studied properly in the past. Generalisations and conclusions had been made based on accepted geohydrological concepts without determining of whether these really apply to the system.

Quite a number of people has the understanding that a groundwater system has to be used before we can understand the system fully. This may be true in some situations – i.e., the development of a wellfield. The risk may be too high to allow other uses, such as a mine with all its associated

impacts, to test whether it would impact a groundwater system and in which ways. This understanding can cause us to destroy groundwater systems to the extent that we will never truly understand the system, and it will never be remediated to a level of functionality – especially given the fact that we did not properly understand the system to begin with. The West Coast Aquifer System are no exception. It may just be a little more sensitive to certain land use / groundwater use activities than others.

The journey into discovering the secrets of the West Coast Aquifer System began with one small investigation into 12 geosites. The first key that was used to unlock these secrets was water levels. The first water levels recorded for the area was in the early 1970s, with the bulk of the monitoring work being done in the early 1980s. The monitoring was discontinued in 1991 as management was of the opinion that we have complete understanding of the system. It was resumed in 1998 for a limited area around the development of the Langebaan Road wellfield to provide additional water for the West Coast District Municipality for the operations of Saldanha Steel (now Arcelor Mittal). At the time the wellfield was developed there was an outcry by the public that the abstraction at the wellfield will potentially affect the Langebaan Lagoon – which had since been declared a RAMSAR site. The development was defended using the conceptual model by Timmerman (1985) that had a no-flow boundary between the Langebaan Road and Elandsfontein Aquifer Systems as an argument as to why the abstraction at the Langebaan Road wellfield would not affect the Lagoon.

The delineation of the four aquifer units in the West Coast Aquifer System is linked to but should not be limited to the extent of the palaeochannels. The Adamboerskraal Aquifer Unit roughly covers the area between the Berg River, Kuilders River, Piketberg mountains, the Papkuils River and the coast. The Langebaan Road Aquifer Unit covers the area between the Berg River, the coast to the north, the granite outcrops around Vredenburg, Saldanha Bay and a line that runs from Langebaan to Hopefield. The Elandsfontein Aquifer Unit lies south of the Langebaan-Hopefield line, between the shale outcrops around Hopefield and the granite outcrops around Darling and the Langebaan Lagoon. The possibility exists that the area south of Geelbek may be part of the Elandsfontein Aquifer Unit when considering the bedrock topography from Roberts and Siegfried (2014). The Grootwater Aquifer Unit is the area between the Yzerfontein-Darling road the granite outcrops to the east of the R27, the Modder River to the south and the coast. There is hydraulic connection between the four the aquifer units, but this does not necessarily equate to flow between the units (Seyler, et al., 2016).

All the aquifer units are layered with a bedrock, a semi-confined to confined layer, a confining layer and an unconfined layer (See Figure 130, Figure 131, Figure 132 and Figure 133). The exact formation that constitutes the different layers may vary, together with their associated characteristics. The layers are not sandwich layers of equal thickness extending over the whole of the area. The layers are dependent on the depositional environment in which it was formed. It will therefore vary in thickness and distribution and may even be absent in places. The geological logs

that are available, are not always reliable, making it difficult to determine the extent of some of the layers.

The bedrock formation consists of either granite from the Cape Granite Suite, or Malmesbury shale of the Tygerberg or Swartland Terrane (depending on which side of the Colenso Fault), or both. The lower aquifer layer consists of Elandsfontyn Formation that consist of angular gravels and sands, that tends to become finer upwards moving gradually into clays and peats. The Elandsfontyn Formation does not form an extensive layer in Grootwater Aquifer Unit, as it only occurs at the confluence of the Modder and Kransduinen Rivers (Timmerman, 1985a).

Figure 130 shows a cross section from north to south through the Langebaan Road and Elandsfontein aquifer units. The layers encountered in the two units are similar, but of varying thickness. The Witzand Formation are not found on the Langebaan Road aquifer unit but can be found on the higher dunes in the Elandsfontein aquifer unit. Relatively young dunes can be found on the Elandsfontein aquifer unit but seems to be absent on the Langebaan Road aquifer unit. It is possible that the agricultural activities on the Langebaan Road aquifer unit have led to the removal for some of the dunes, similar to the situation at Cape Flats, or that the dunes were never deposited at all. The latter is a more reasonable explanation. Calcrete layers are found at both aquifer units, but it has never been seen as an important factor in the geohydrology of the Lower Berg River Aquifer System. When looking at the water level graphs for the Langebaan Road aquifer unit, it would seem that there is four layers that make up the unit. The first would be bedrock, with the shale granite contact almost splitting the palaeochannel in two – the upper part closer to the Berg River with shale as bedrock and the lower half of the channel closer to Saldanha Bay with a granite bedrock. These water levels seem to interact with the confined layer above, as there is a similarity in the patterns. The bedrock is overlain with the sediments of the Elandsfontyn Formation, which show the effects of the activities at the wellfield, whether abstraction or MAR through injection. The next layer is made up of the Saldanha Formation, and the Varswater Formation. The water levels in this layer seems to respond to rainfall events but with a time lag of at least 3 months. If one looks at the water quality of this layer, it seems to be better than one would expect from an unconfined aquifer in a coastal aquifer. In the Elandsfontein aquifer unit, the water quality in this layer was at times even better than that of the lower Elandsfontyn Formation layer. The last layer – based on the patterns observed in the water level graphs – seems to be a very shallow system that responds quickly to recharge. This group includes almost all the dug wells, that is in most cases only 10m deep with calcrete forming the base of the dug well. During the recent drought dug wells and most of the springs dried up completely.

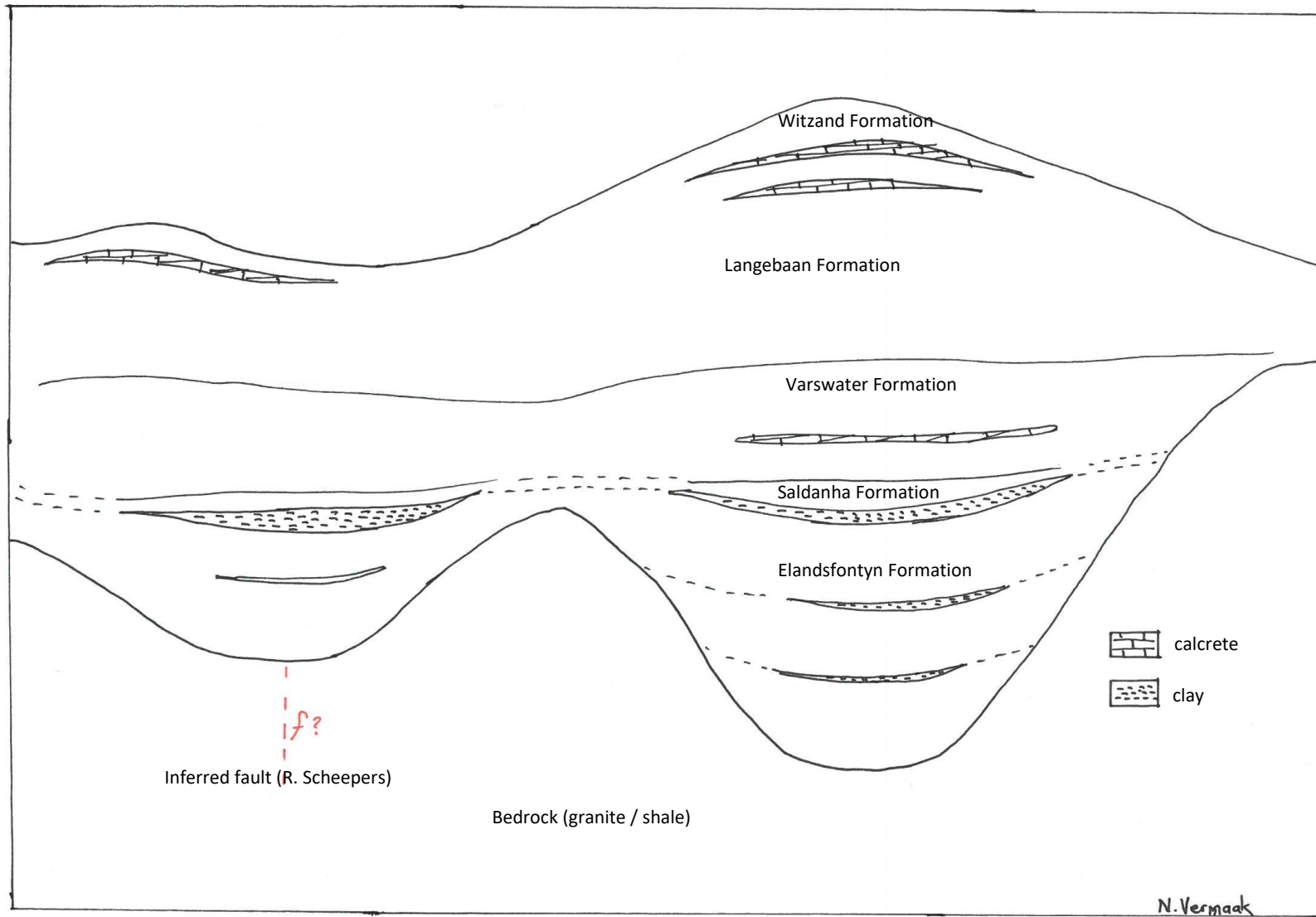


Figure 130: Conceptual cross section through Langebaan Road and Elandsfontein Aquifer Units (conceptual understanding; not to scale).

It is thus possible that the calcrete layers may create a semi-confined layer in what is traditionally considered to be the upper aquifer layer. The calcrete, because of its characteristics, would act as an aquitard, but it also has the potential to store a large amount of water. In the Elandsfontein aquifer unit, the watertable for the upper aquifer layer is just below the second calcrete layer. This seems to indicate that the calcrete slowly releases the water stored within its pores to the underlying sedimentary deposits. It also seems to protect the water quality of the underlying aquifer layers by reducing the influence of the seaborne salt.

The 1:50 000 geological map for Saldanha shows an inferred fault line by R. Scheepers in Saldanha Bay. This fault line should then be continuing inland underneath the Langebaan Road palaeochannel, and it was thus included in the representations of the conceptual model. There is a second inferred fault by R. Scheepers indicated parallel with the Langebaan Lagoon. This seems to agree with the information shared by Cherry (2016) about other fault lines on either side of the Colenso Fault Line and may be part of the Colenso Fault System.

Figure 131 is a cross section of the Elandsfontein aquifer unit from west to east showing the conceptual understanding of the different layers that make up the aquifer unit. The extent of some of the layers have not been determined properly, but borehole logs seem to indicate that the clay layer disappears in the vicinity of the R27. The last borehole where clay was recorded in the log was BH4. BH2 and BH2A at Geelbek seem to be separated by a thick calcrete layer rather than a clay layer. Figure 132 plots the conceptual understanding of the Adamboerskraal and Langebaan Road aquifer units, from west to east, ending at the mountains north of Aurora. There are clearly similarities between the two sketches. In both sketches that approximate location of the Colenso Fault and the inferred faults are indicated.

The Grootwater aquifer unit is a link between the Atlantis aquifers and the three aquifer units further north. The formations that make up the layers are a reflection of this (Figure 133). The impact of dune formation is also clearly visible, leaving a terraced landscape. The fact that very few of the rivers on this part of the coast reaches the sea, shows the impact of the dune formation on non-perennial rivers that does not generate enough run-off to clear the rivers from dune sediments. Most of the rivers disappear into the dunes, or end in coastal wetlands. The Elandsfontyn Formation has only been seen in the logs of a number of boreholes on the southern end of the Grootwater aquifer unit, just north of the Modder River. The Modder River originates in the granite hills above Mamre and is the largest river in the area of the Grootwater aquifer unit. When looking at the pans and wetlands in the Grootwater aquifer unit, as well as the granite intrusions from the Darling Pluton, it would seem that there may be at least two fault lines below the Grootwater aquifer unit (See Figure 49 for additional information). The water quality of the Grootwater aquifer unit also distinguished it from the other units that make up the Lower Berg River aquifer system. The water quality of the aquifer unit is very good, despite its proximity to the coast. It is only boreholes that is less than 2km from the coast that has a higher EC of 200mS/m or more. The ECs of the rest of the boreholes are below 10mS/m. The parameter that was most surprising, was the pH that was measured in the field with an Extech DO 700 multi-meter. Most

of the boreholes had pH measurements below 6, which places it in the acidic range. The pH measurements of the other aquifer units are 7 or above, indicating the influence of the calcrete on the water quality. The low pH measured at Grootwater could indicate the influence of the vegetation or a possible link to the TMG aquifers, where a low pH is characteristic of the formation.

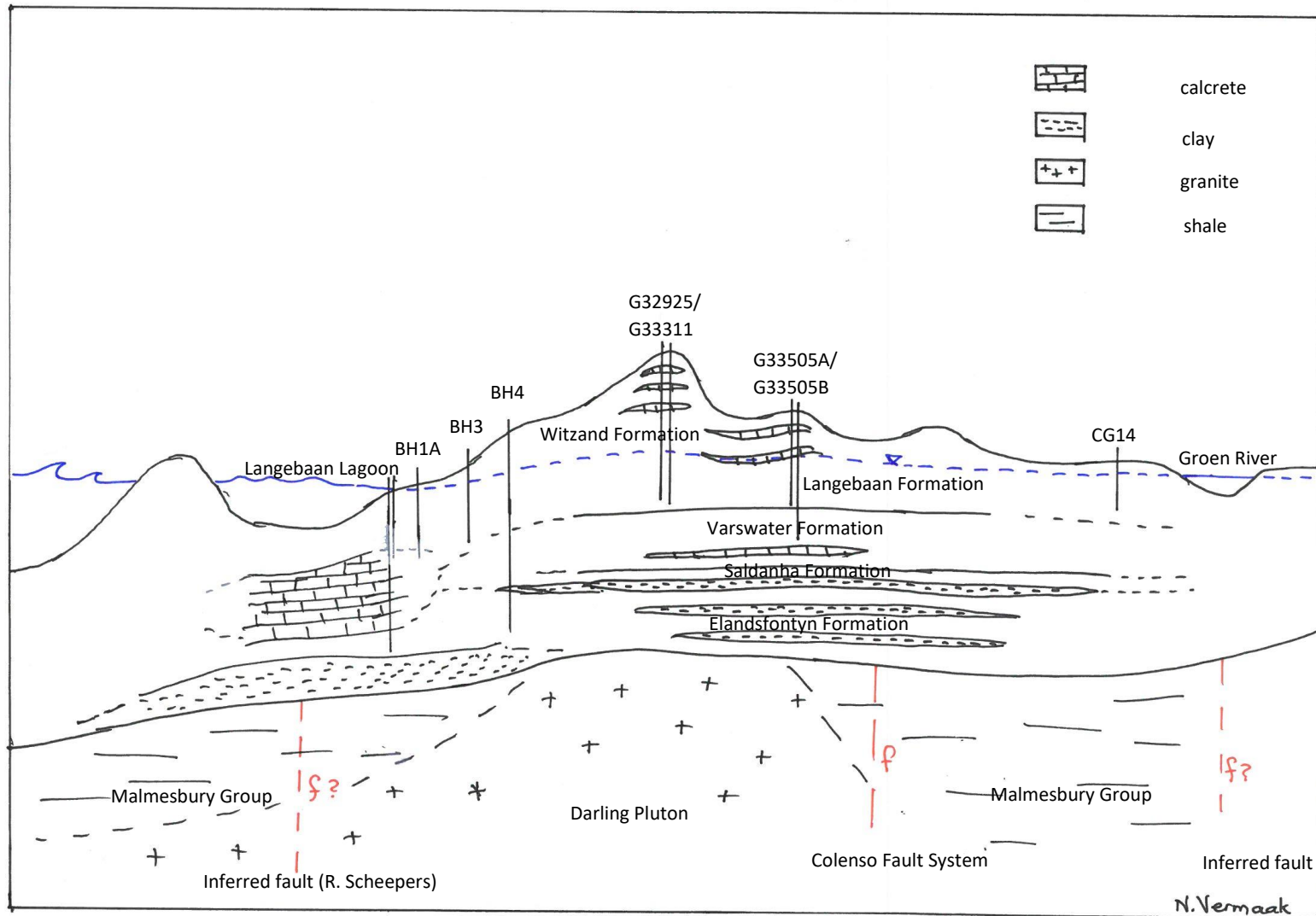


Figure 131: Cross section through the Elandsfontein Aquifer Unit - a conceptual understanding (not to scale).

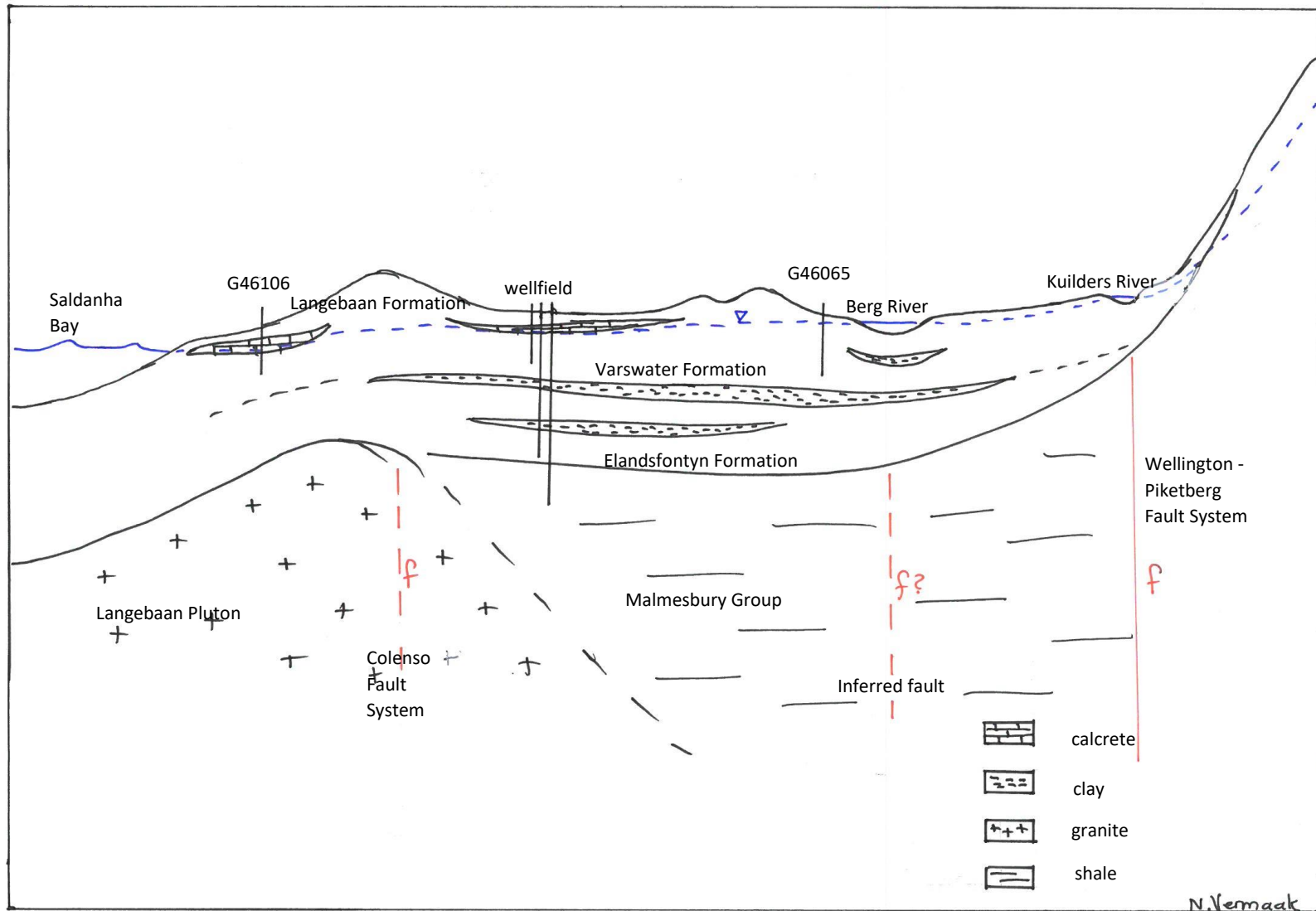


Figure 132: Cross section through the Adamboerskraal and Langebaan Road Aquifer Units - a conceptual understanding (not to scale).

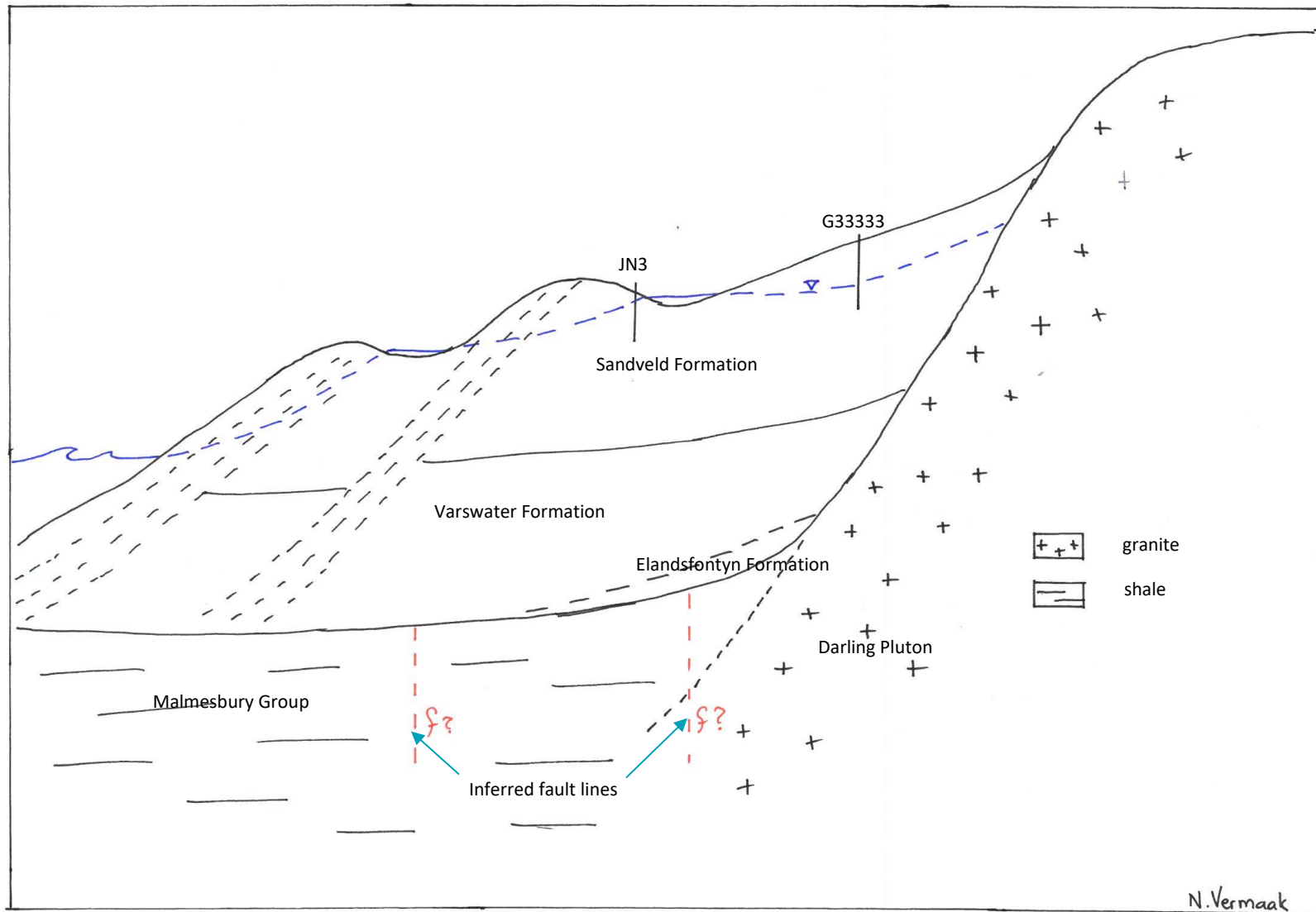
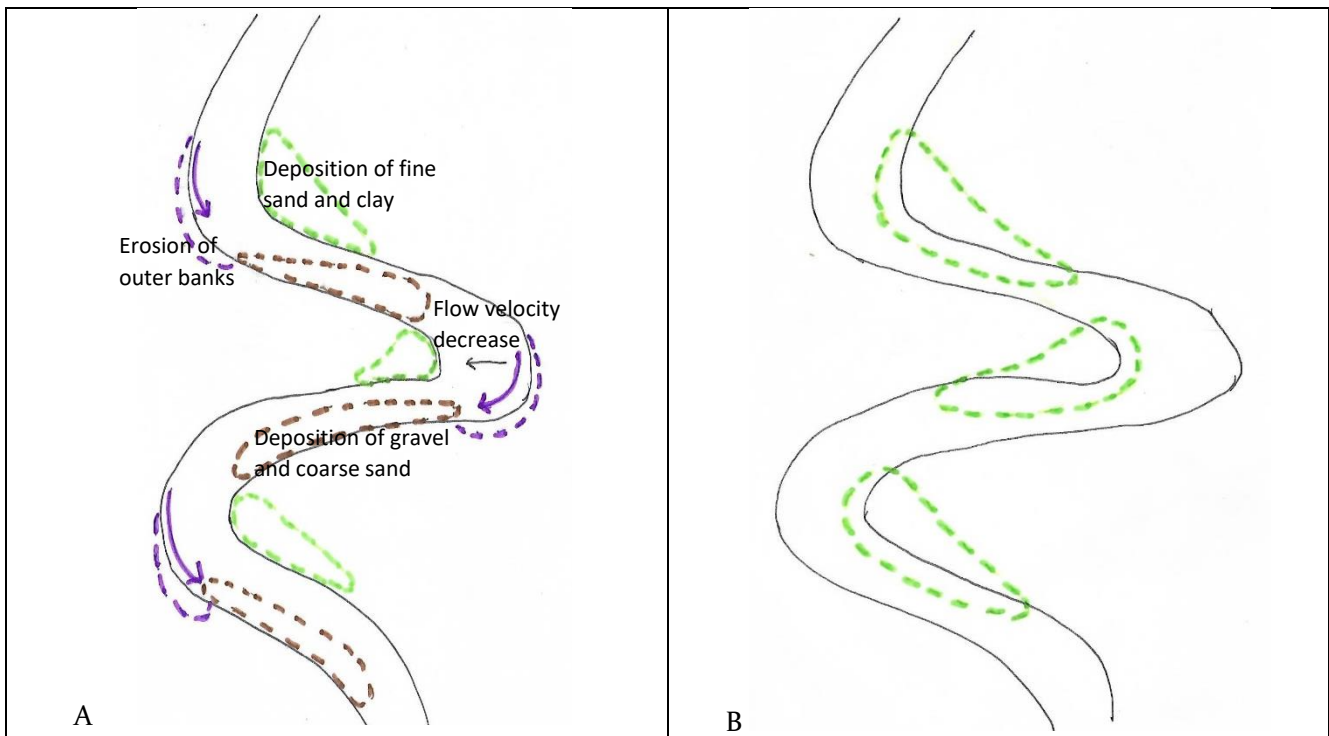


Figure 133: Cross section through the Grootwater Aquifer Unit - conceptual understanding (not to scale).

A knowledge of sedimentology and geomorphology is helpful in order to understand the layers of the Cenozoic deposits. This makes it easier to explain why there are times when the clay layer or the gravel layer are absent. What follows is a bit of an explanation about the processes that are involved (See Figure 134).

The speed of the flow of water in a meandering river is the highest on the outside of the bend, decreasing towards the inside. This means that there is a scour zone on the outside bend, that may lay the bedrock bare. It is also where erosion takes place, that provides the material for deposition further downstream (Figure 134A). Deposition of clay and fine sand takes place on the inside of the bend, while gravel is deposited on the outside since the higher velocity can carry the larger heavier particle further. Figure 134B – E looks at how the deposition of the fine sand and clay as the flow path of the river changes. Over time, the river may breach the meander in the river, cutting off the outer bend (Figure 134D). Oxbow lakes are thus formed on the outside of where the river used to flow, with lenses of clay and gravel to mark the changes over time. This may mean that it is possible to have the Elandsfontyn clay close to bedrock in some instances with no gravel. The clay occurs in lenses that does not necessarily coincide with the gravels, and vice versa. Figure 134F provides a conceptual understanding of the position of the clay and gravel lenses compared to one another, showing that it does not always coincide.



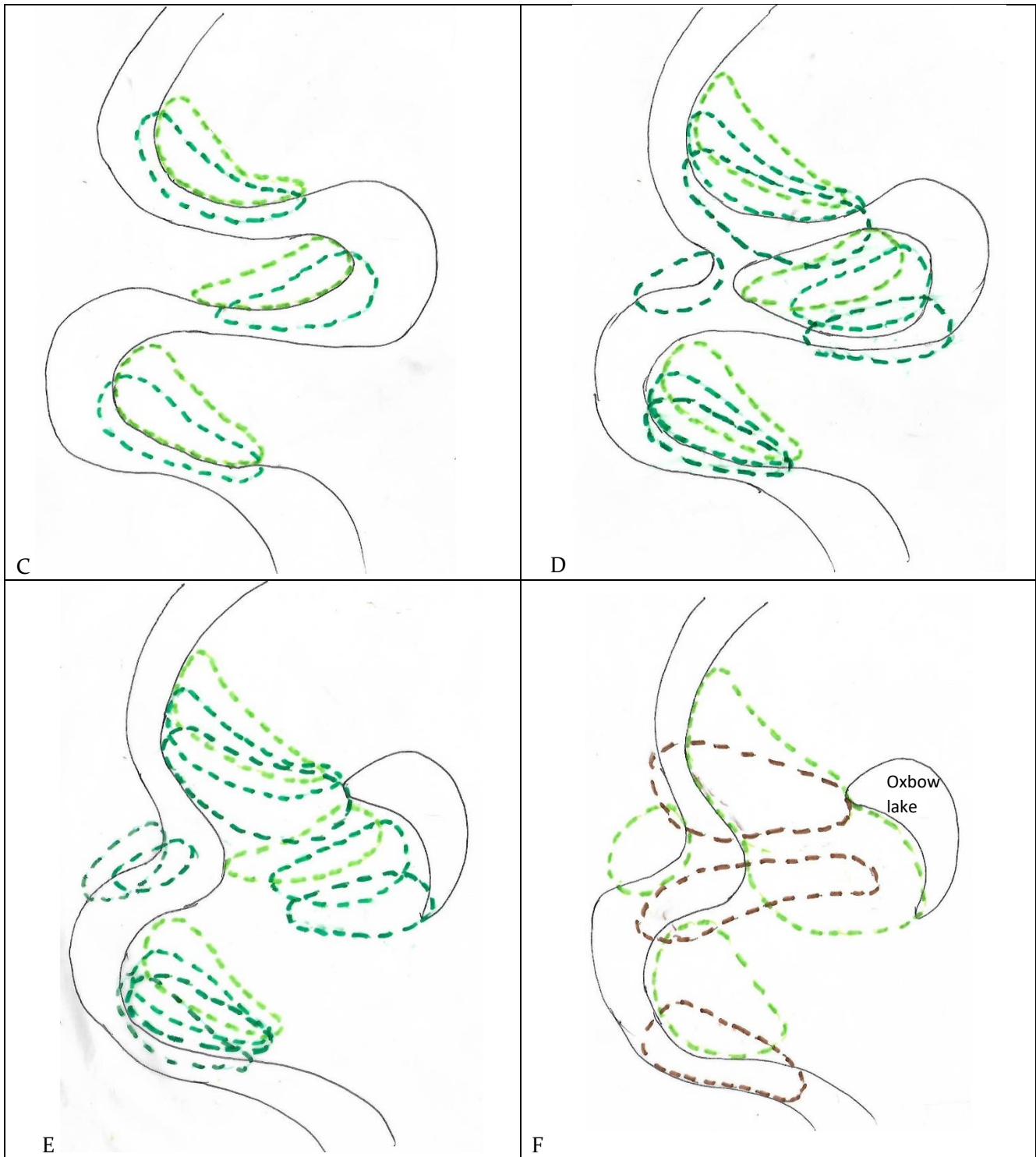


Figure 134: Changes in a meandering river over time and how this affects the deposition of sediments.

There are various springs, depressions, wetlands and pans along the palaeochannels. These may be the remnants of the oxbow lakes that formed at the outer edge of the meandering rivers that formed the palaeochannels. Similar springs, wetlands, pans and depressions can be seen along the Groen and Brak Rivers, as well as the Berg River.

When taking the description above into consideration, it is very clear that the layers are not neat, horizontal layers set down in the palaeochannel. An updated version of Figure 130 would look like the cross section in Figure 135. This includes changes in the basement based on recent investigations. A borehole that was drilled into the middle of the palaeochannel will then still fit the description given by Timmerman (1985b) of three upward fining layers, beginning with gravel, sand and ending with clay. It would, however, be made up of intersecting layers and would thus not be representative of the whole system. Boreholes on the outer edge of the palaeochannel may not intersect clay at all, or the clay may represent weathered bedrock rather than clay that was deposited in the palaeochannel.

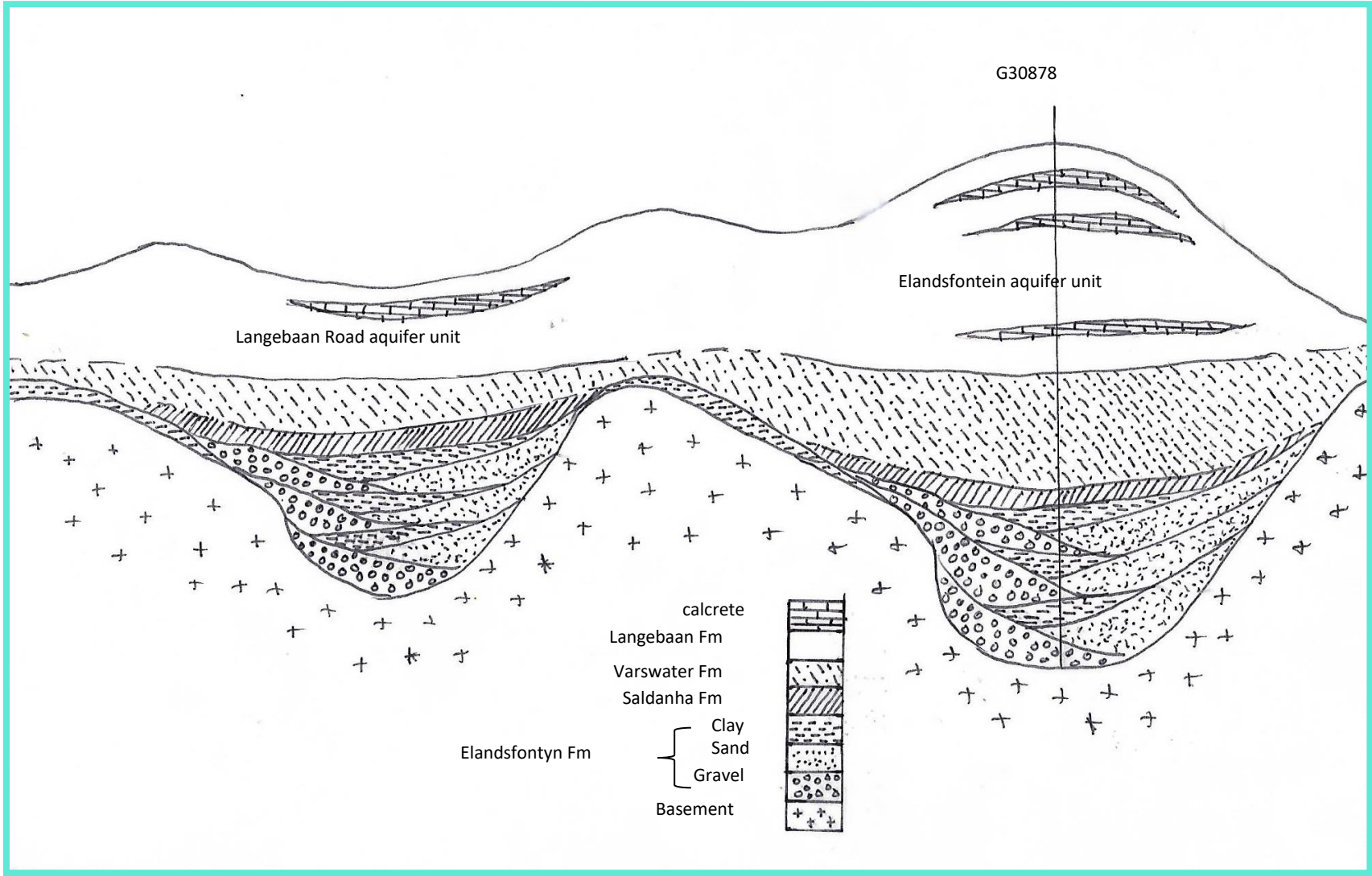


Figure 135: Cross section through the Langebaan Road and Elandsfontein aquifer units, taking the sedimentology into account (not to scale).

The quest to determine the natural recharge area has not been very successful to date. Vermaak and De Haast (2013) used the conceptual model by Tredoux and Engelbrecht (2009) (Figure 71) and the EC readings obtained during field work (Table 22), to determine possible local recharge areas. Figure 136 shows the location of geosites used during the study. The topography profiles shown in Figure 137 and Figure 138 was plotted using the function in Google Earth. The location of the boreholes was plotted on the cross sections. Both the higher elevation and the EC values seemed to indicate that the higher lying areas in Elandsfontein aquifer unit and the Hopefield area might contribute to recharge of the aquifer units. The Stiff plots (Figure 123) shows a correlation between the water quality in the Elandsfontein aquifer unit and the basement and deep boreholes in the Langebaan Road aquifer unit. This may be an indication that there is some recharge through the basement and the shale-granite contact. The question still remains whether the majority of the recharge is linked to local rainfall events or from further away.

The results of Smith (2016) and Andries (2019) seems to indicate the two opposites, with one indicating recharge from further afield and the other local recharge. Results from study by Andries (2019) also seems to indicate that recharge does not come through the basement aquifers, while the water quality analysis shows a high correlation between the Elandsfontein aquifer unit and the basement and deep boreholes in the Langebaan Road aquifer unit. Analysis of the monitoring data seems to indicate recharge from various sources. This would include recharge through the faults and fractures, through the weathered basement, from the river and from local rainfall. The high soil water repellency in the study area may be a factor that affects the volume of local recharge, while the location of most of the fault lines are not certain and real data is limited. More information is clearly needed in the determination of the natural recharge area. The recharge volume is almost as big a mystery as the natural recharge area(s). Original estimations were much higher than the more recent work. It is possible that the lower recharge may be linked to the lower rainfall recorded in recent years. Solving this mystery can provide important information that will lead the more effective and sustainable management of the groundwater resources. It is possible that cluster analysis of the available hydrochemistry datasets could be used to verify the recharge mode and potential source area(s), should thus be done in future work. Determining the natural recharge sites can potentially lead to the selection of more optimal sites for MAR to augment the groundwater supply.

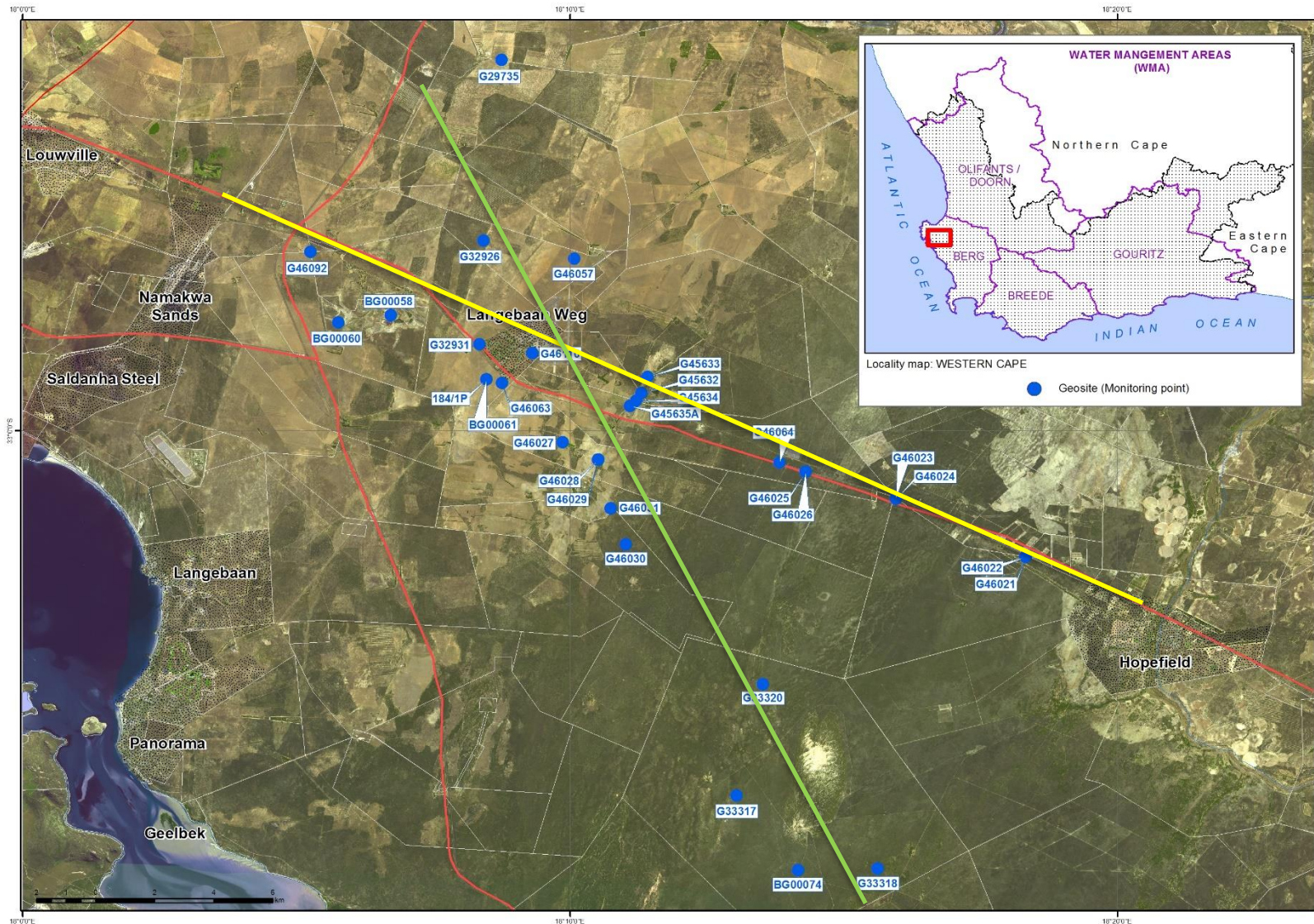


Figure 136: Map showing the boreholes used in the two transects, as well as other boreholes of importance, i.e. the LRA wellfield boreholes. (Hopfield transect—yellow line; Darling transect—green line) (Vermaak and De Haast, 2013).

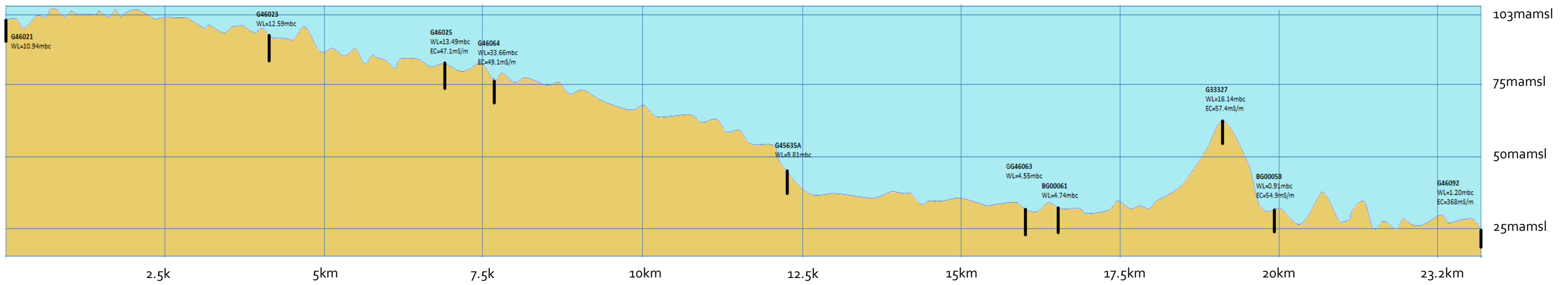


Figure 137: Transect showing boreholes from the proposed Hopefield recharge area past the LRA wellfield with the latest monitoring data (Vermaak and De Haast, 2013).

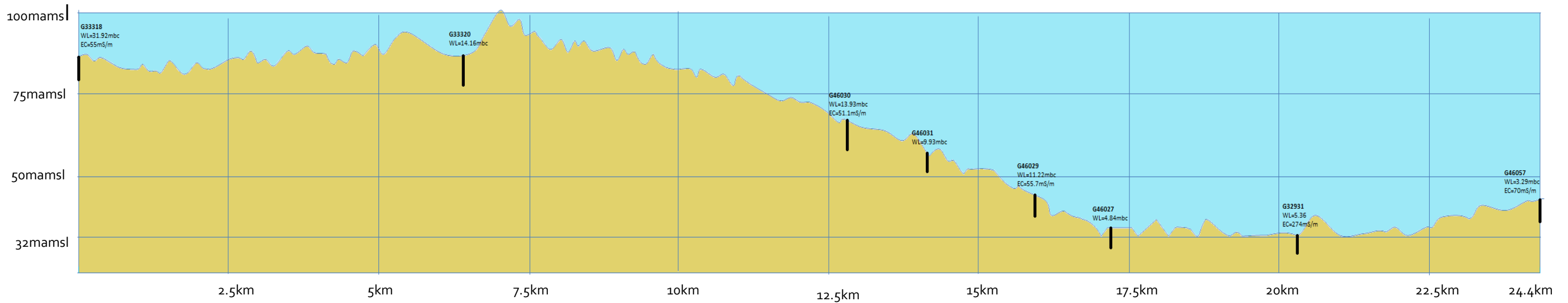


Figure 138: Transect showing boreholes from the proposed Darling recharge area past the LRA wellfield with the latest monitoring data (Vermaak and De Haast, 2013).

Table 22: EC values for Hopefield transect and Darling transect (Vermaak and De Haast, 2013).

Site ID	Hopefield	Site ID	Darling
	EC [mS/m]		EC [mS/m]
G46025	47	G33318	55
G46064	49	G46030	51
G33327	57	G46029	56
BG00058	55	G32931	241
G46092	368	G46059	70

One of the potential sites for MAR could be in the floodplain of the Berg River. Figure 139 shows and illustration of the possible link between the current river channel and the palaeochannel of the Berg River. The conceptual model is based on the premise that the current river channel will have similar sedimentary layers as the Langebaan Road-Adamboerskraal aquifer unit that underlie it. It is also based on the fact that the last significant natural recharge of both the upper and lower aquifer layers of the Langebaan Road aquifer unit took place in 2007. It was also the last year that there were big floods in the Berg River (Figure 125) and before the completion of the Berg River dam.

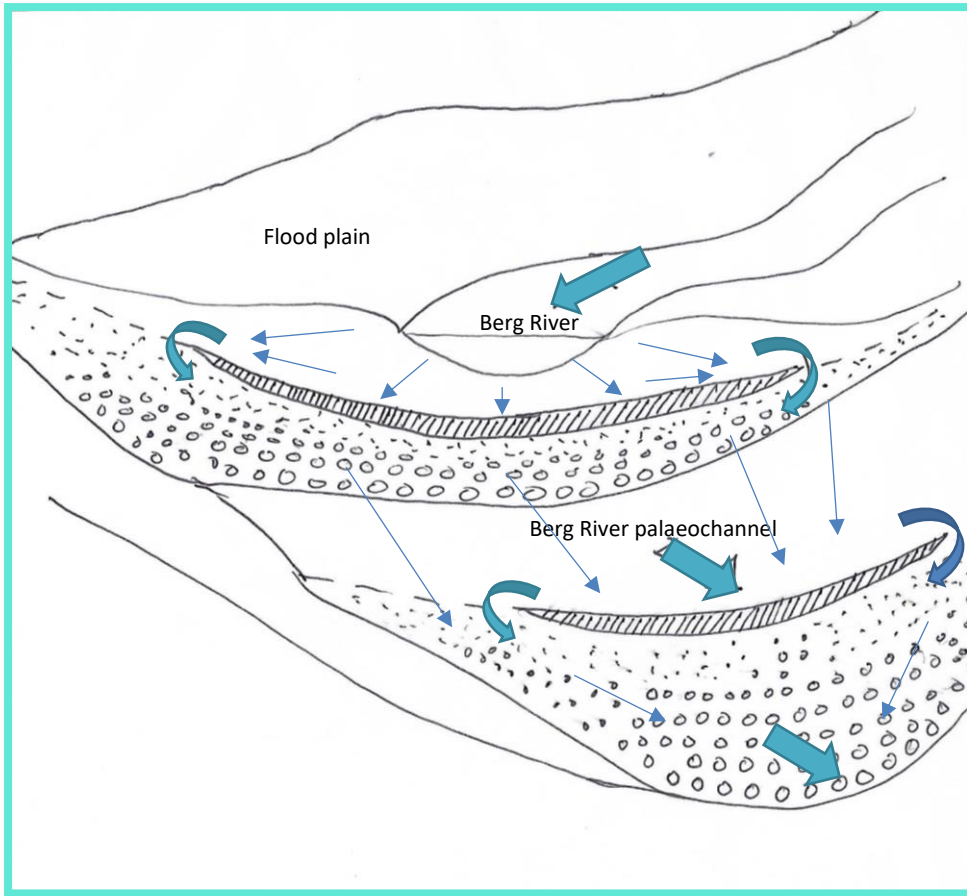


Figure 139: Illustration showing the possible interaction between the current Berg River channel and the palaeochannel of the Berg River below it.

One of the puzzles that lead to the development of the conceptual model as presented above is the fact that both the upper and lower aquifer layers of the Elandsfontein aquifer unit responded to the abstraction at the Langebaan Road wellfield. If the clay layer completely separated the Elandsfontein Formation from the Varswater Formation, this would not have been possible. The illustration in Figure 140 provides an explanation as to how it would be possible for both the upper and lower aquifer layers of the Elandsfontein aquifer unit to respond to the abstraction. The clay layer of the Langebaan Road aquifer unit thins out at the edges, which means that to some extent it will influence the water levels of the upper aquifer layer of the Langebaan Road aquifer unit. It would potentially have a greater impact on both aquifer layers of the Elandsfontein aquifer unit, where the clay layer is also absent at the edges of the palaeochannel. It is also possible that the greater abstraction will also impact the groundwater stored in the upper aquifer layers of the Langebaan Road aquifer unit itself, which would thus corroborate the observation of the farmers that their dug wells were drying up. The conceptual model illustration in Figure 135 may seem to contradict the illustration below (Figure 140), but the clay that formed as a part of the weathering of the bedrock varies in thickness and does not exclude the possible linkage between the two aquifer units, as it is the clay lenses in the palaeochannels itself that is important.

The shale-granite contact also adds an additional potential pathway for groundwater flow.

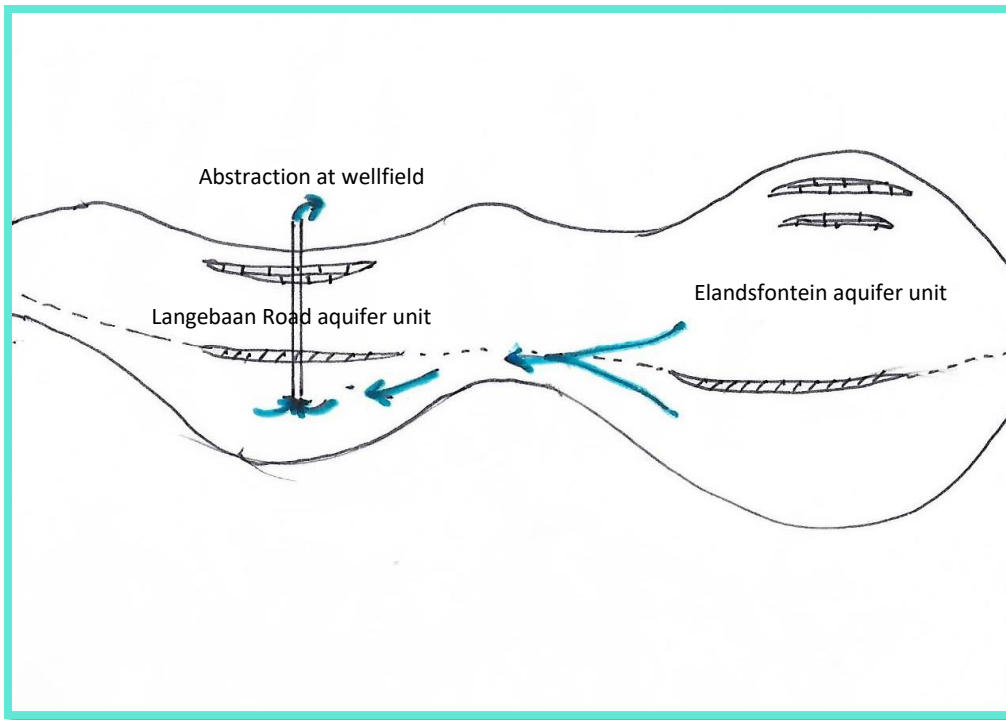


Figure 140: Illustration to explain why both the upper and lower aquifer layers of the Elandsfontein aquifer unit responded to the abstraction at the Langebaan Road wellfield.

5.3 Geological Conceptual Model

A simplified 3D geological conceptual model was constructed using two data sets from Timmerman (1985a; 1988). The data sets were used since the lithostratigraphic layers were identified together with the information to translate the layers in relation to mean sea level. The data was then pulled into WISH (Lukas, 2012) where topographical surfaces were generated for the top of each layer. Figure 141 shows the top layer that was generated. The coastline was not included in the analysis, and the Darling pluton was not included because of a lack of information. These layers were used for the development of a 3D model of the system (Figure 142). The highest dunes are on the Elandsfontein aquifer unit, with high dunes on the Farm Kransduinen on the southern edge of the Grootwater aquifer unit.

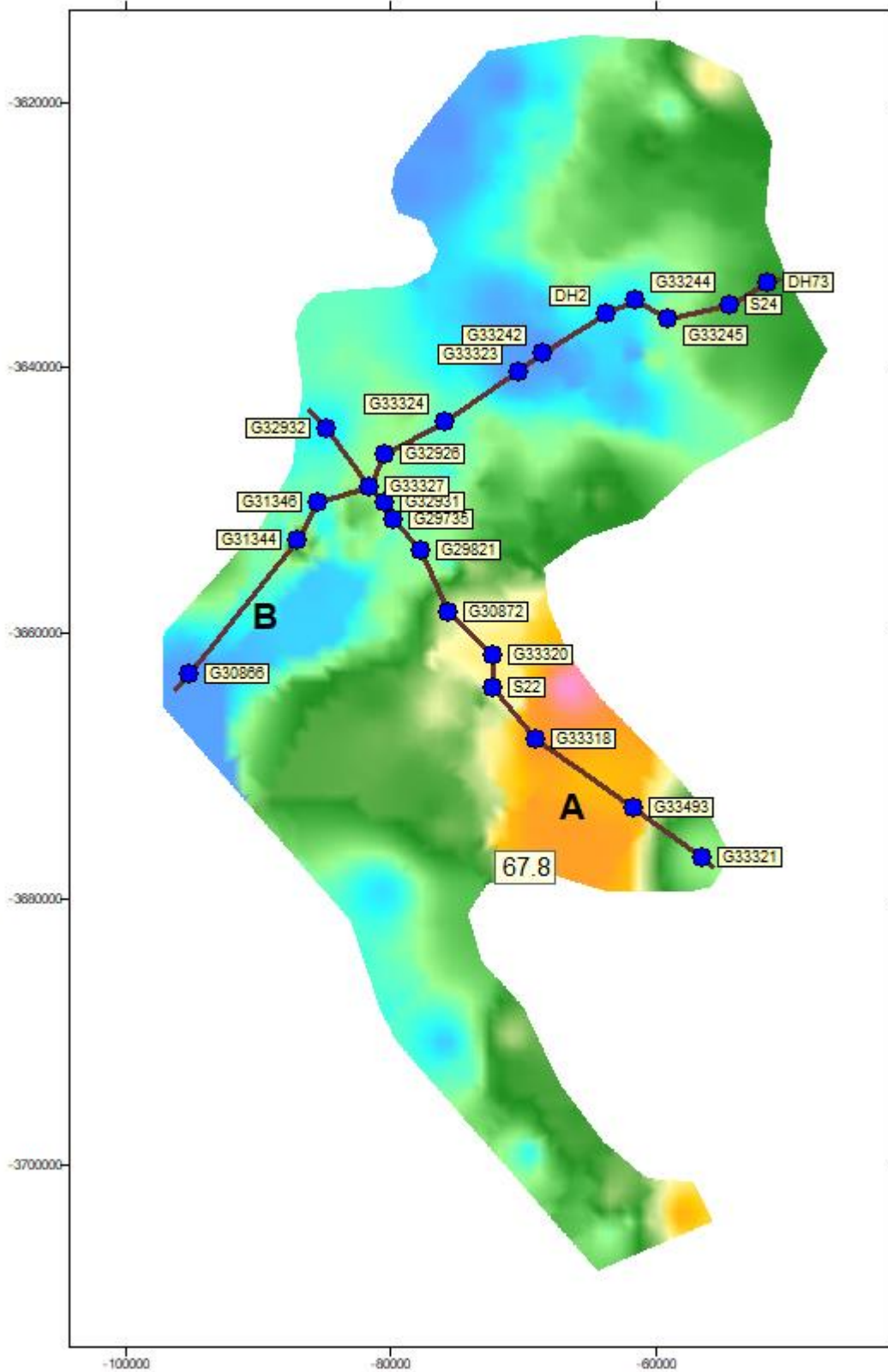


Figure 141: Top layer (generated with WISH; Lukas, 2012).

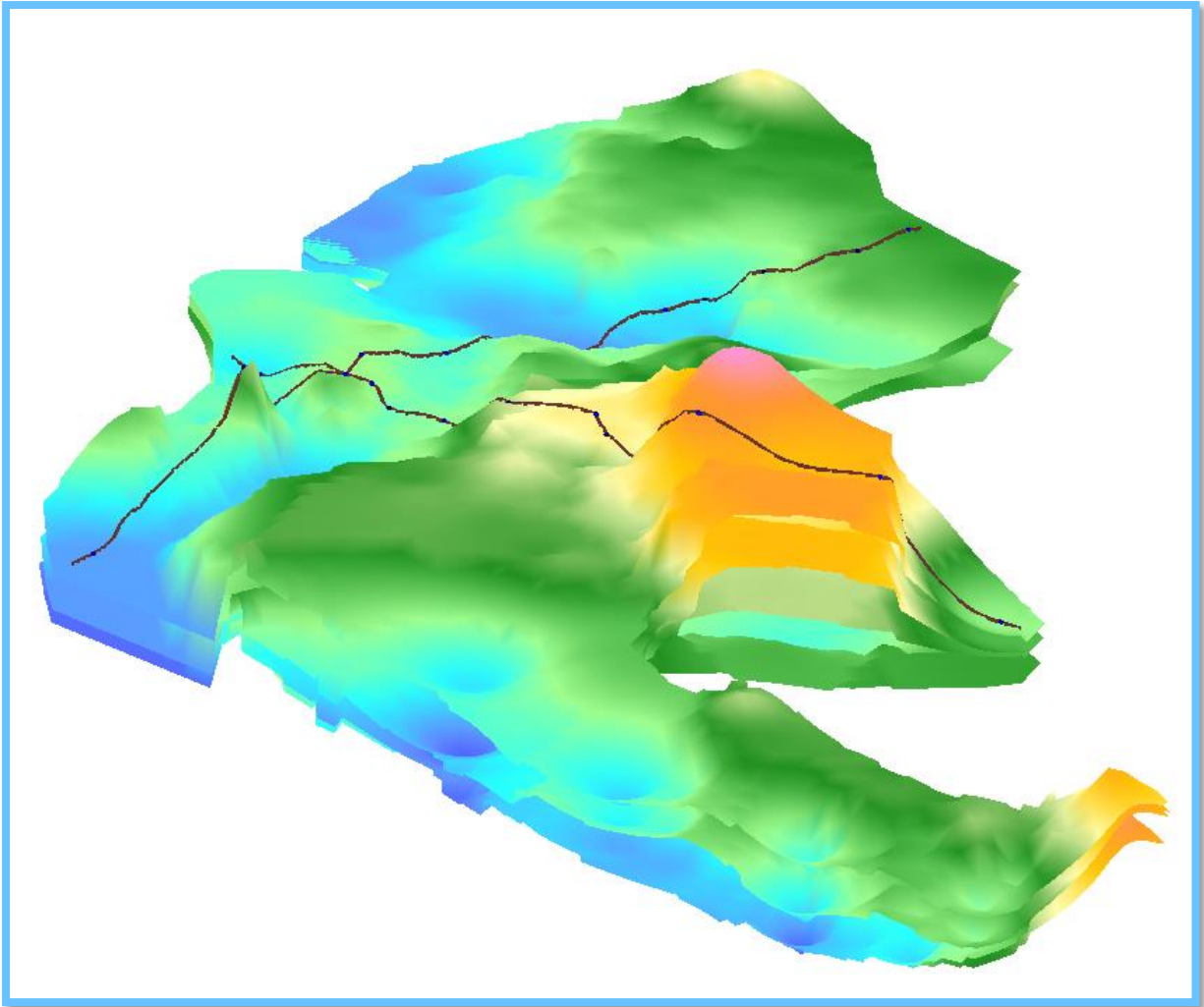


Figure 142: Three-dimensional model of the Lower Berg River aquifer system (generated in WISH; Lukas, 2012).

Two cross-section lines were chosen (see Figure 141), based on the boreholes with the relevant data and to provide the best possible information about the aquifer system (Figure 143). The clay layers from the Elandsfontyn Formation and the calcrete layers of the Langebaan Formation were not added. This level of complexity should be included when the exercise is repeated with geological modeling software. Cross section A runs from southeast to northwest, with the Elandsfontein aquifer unit on the left-hand side of the drawing and Langebaan Road aquifer unit on the right. It covers a distance of 47,264km. G33320 is at the basement high that Timmerman (1988) identified as the dividing line between the Langebaan Road and Elandsfontein aquifer units. The Elandsfontein phosphate mine is between G33320 and S22. S22 is located close to G33317 and G30878. The old Samancor phosphate mine would be more or less between G33327 and G32932. The palaeochannels are not very clear in this cross section and the basement high that separates the two palaeochannels are not very significant. This may be because of the point selected for the cross section. Different results are possible if a North-South line was chosen. The deepest points of the two palaeochannels is at S22 (Elandsfontein) and G33327 (Langebaan Road). The Varswater Formation is also at its

thickest at these two points. The highest point of the cross section is at G33318 (just over 100mamsl), which is in the vicinity of the fossil rich dunes on the Farm Elandsfontein. The Elandsfontyn Formation is continuous, while the Varswater and Langebaan Formations tapers off and are absent at certain points along the cross section.

Cross section B is in a west to east direction, spanning a distance of 60km. G30866 is on the Potsberg peninsula on the other side of the Langebaan Lagoon. The section between G30866 and G31344 is thus not a true reflection of the situation. The basement high at G31344 was surprising but at further inspection it was found to fall on the same line as the boreholes drilled into the Colenso Fault System on either side to the northwest and the southeast. The old Samancor phosphate mine, now the West Coast Fossil Park is between G31346 and G33327, where the Varswater Formation is at its thickest. The Langebaan Road Wellfield is more or less in line with G32926, but further south. The Berg River flows between G33323 and G33242, with both boreholes within the wide floodplain of the river. The Elandsfontein Formation, and thus the palaeochannel, is continuous below the Berg River. The Varswater Formation is clearly absent in the Adamboerskraal aquifer unit. The deepest part of the palaeochannel is at G31346 in the Langebaan Road aquifer unit (at about -50mamsl), with the deepest part of the palaeochannel at the Adamboerskraal aquifer unit is a G33244.

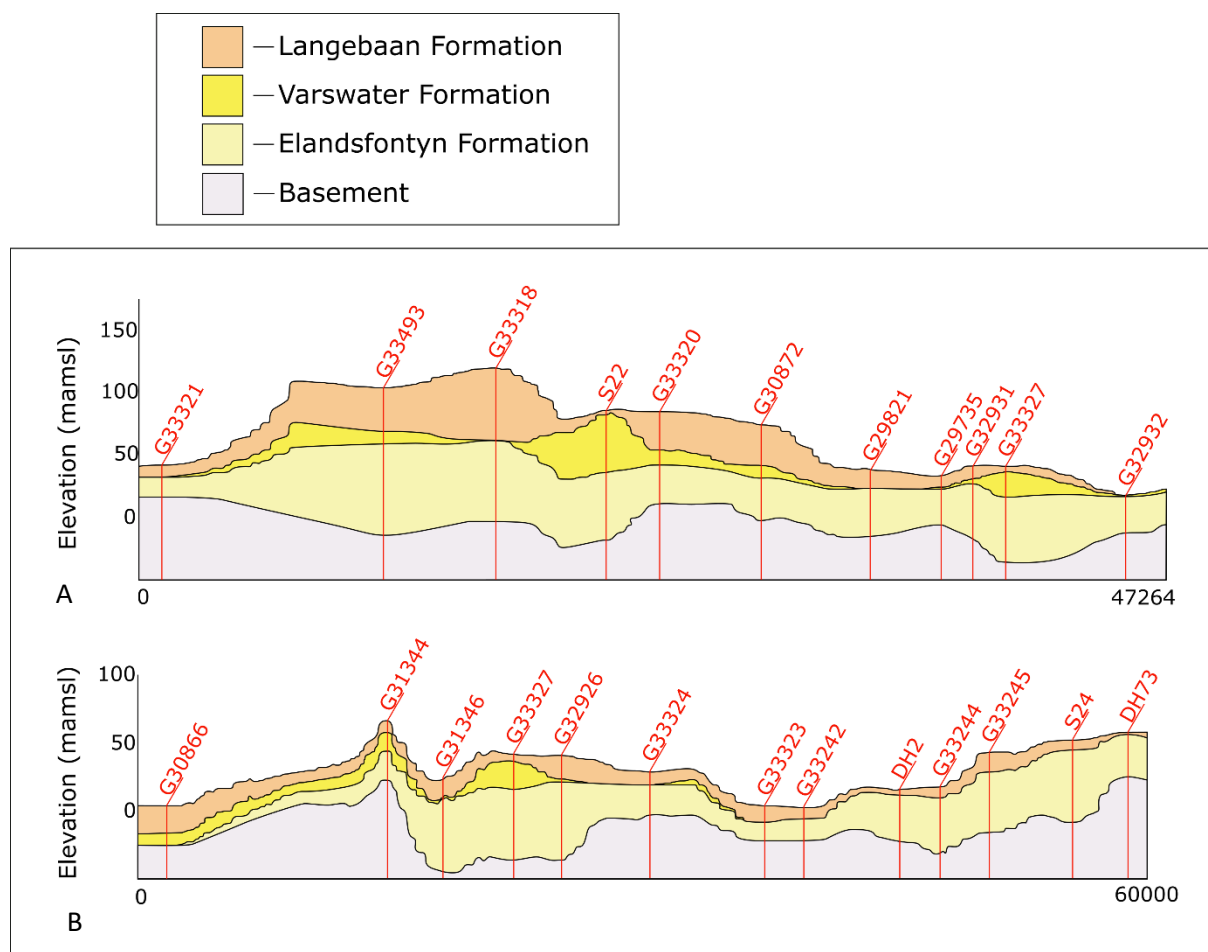


Figure 143: Simplified cross-sections showing the different geological formations.

Further analysis of the available geological data would be necessary, and it would be important to incorporate the other lithological logs of boreholes drilled in the late 1980s and onwards. This would help to provide a clearer picture of the aquifer system and its interconnectedness. Incorporating historical geophysical data and the recent would further contribute to building a proper conceptual model for the study area.

5.4 Summary

Conceptual models should grow and change over time since it is not possible to know everything about the system from the beginning. The Timmerman conceptual model was very detailed and provided a good foundation from which to work. There were, however, a number of assumptions that was made by Timmerman that has since proven invalid. Every successive scientist added to our understanding of the system. The conceptual model presented in this document built on the work of each of them, and used the experience and observations made to expand on their work. It would be necessary to do further scientific work to quantify and prove some of the elements of this conceptual model, but it is the best explanation that can be given for some of the observations made. The conceptual model is, however, important for the development of a numerical model, and the assumptions made can mean the difference between a model that is close to the real system, or one that fails to explain the measurements. The following chapter will look at some of the models that have been developed for the Lower Berg River Aquifer System, and evaluate it based on current understanding.

Chapter 6: Model evaluation



BG00071-RF with breccia linked to the Colenso Fault System in the background (28 August 2017)

A model is an approximation of the real world. Its ability to mimic the real world is determined by the quality of the conceptual model, which in turn is based on the understanding of the exploration and monitoring data. Since it would never be possible to fully understand the natural world a model would remain the best possible version of the real world that can be created.

A number of models had been compiled on the Lower Berg River Aquifer System or parts thereof over the years. Figure 144 shows the progression of models that was compiled, and the work that influenced it. Note that it does not necessarily refer to publications, but rather the person(s) that were responsible for developing it model or the study that contributed to the model. The persons or titles in bold are linked to actual models. There is a series of models not listed in the diagramme. Some are models that was done for the phosphate mine on the Elandsfontein aquifer unit, where permission was required to include it. Below is a more complete list of models with some notes on their conceptual model. Only three models will be evaluated in more detail with an indication how it links with the conceptual model presented in Chapter 5.

Timmerman (1988)

The conceptual model was very detailed. There were a few misconceptions in the conceptual model with regard to no flow boundaries and a few other things. It only covers Langebaan Road and Elandsfontein. It did not consider groundwater surface water interaction. It did not have the advantage of all the monitoring data to use in calibrating the model. The conceptual model used the bedrock elevations from Smith (1982).

Woodford (2009)

Woodford had a good conceptual understanding of the system based on the analysis of the monitoring data for the WCDM. He understood the link between Langebaan Road and Elandsfontein aquifer units as a result of impact of abstraction on water levels at G33320. He also showed that there is interaction between the basement formations and the overlying sediments.

CSIR (Weaver, et al., 1997)

It was based on historical monitoring data. There was a ten-year gap by the time the model was developed. The model used the conceptual model of Timmerman (1988). The model predicted 5m drawdown as a result of abstraction; the actual drawdown was 11m from the original baseline readings. The impact of the abstraction was also felt much wider than model anticipated. It did not predict the impact to the dug wells since a continuous clay layer was assumed. It only included the Langebaan Road aquifer unit.

CSIR (Jovanovich, 2009)

The model still used the Timmerman (1988) conceptual model, and it was only for Langebaan Road aquifer unit.

DWAF (2008)

The model used the Timmerman (1988) conceptual model, with modifications such as the continuation of the palaeochannel to the sea. Dennis (2010) indicated that very few boreholes were included in the setup of the model.

Seyler, et al. (2016)

It is the first model that included all four aquifer units. The model used the basement contours of the bedrock compiled by Roberts and Siegfried (2014) with modifications.

Smith (2019)

This model only covered the Elandsfontein aquifer unit. Early results showed that the findings of the model corresponded with results for isotopes and CRD calculations (Smith, 2016).

Barrow (2015)

This was the basic Elandsfontein model for the phosphate mine and it had no-flow boundaries in area where recharge may come from. This model is linked to the phosphate mine and required permission to use.

Jaco Nel (2019)

The model was also done in connection to the phosphate mine, originally for SANParks. It was later used for the phosphate mine and the Saldanha Bay Local Municipality. No other information is currently available.

Imrie (2016)

The model was developed around the dewatering and MAR processes of the phosphate mine and required permission for inclusion.

Zhang (2019)

This model was developed for WRC project K5/2744 and was not available of review.

A discussion of the models by Timmerman (1988), Berg WAAS (DWAf, 2008) and Seyler, et al. (2016) will follow.

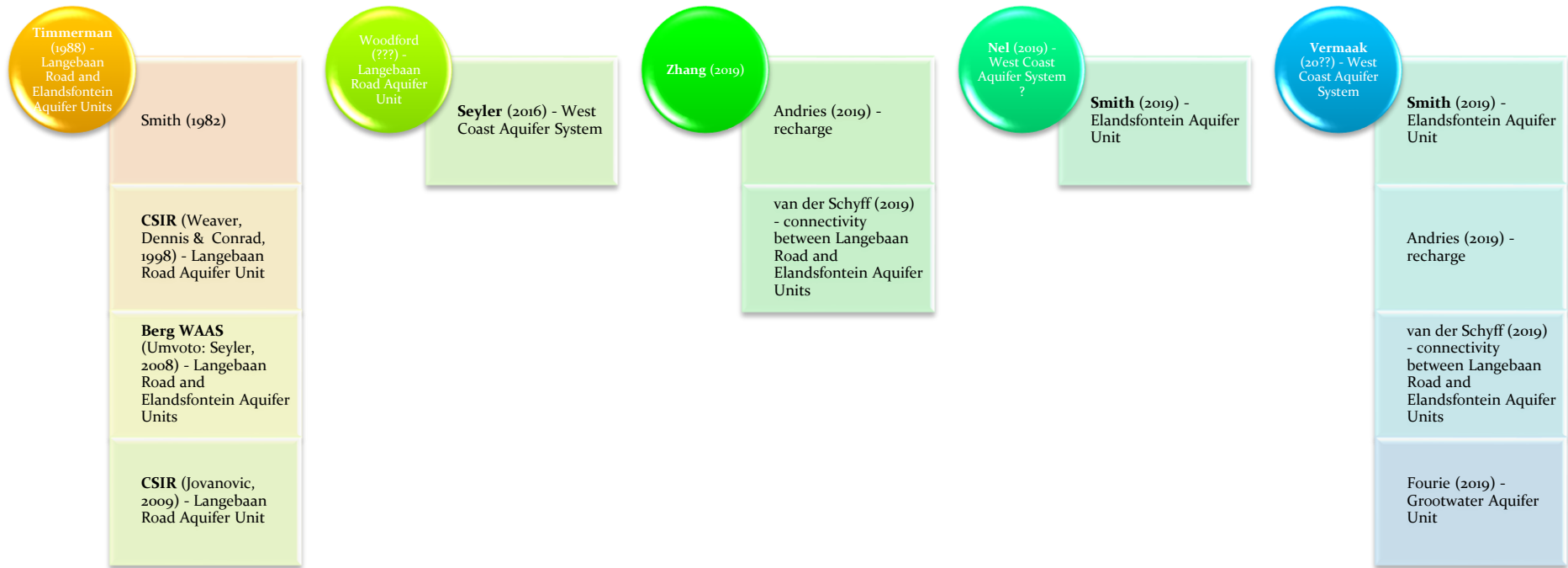


Figure 144: Models of the West Coast Aquifer System, based on conceptual model.

6.1 Timmerman (1988)

Timmerman (1988) developed a mathematical simulation or modelling of the regional groundwater flow to calibrate and verify hydrogeological data that was obtained during extensive regional investigations in the Lower Berg River area. Input variables include the geological data (thickness of layers); hydrogeological data (vertical and horizontal conductivity, storativity); hydrological data (spring and river flow, abstraction rates and artificial recharge) as well as meteorological data (rainfall, evapotranspiration and temperature). Recharge had to be calculated as there were no reliable data from recharge studies available at the time. Rainfall from the weather stations in Darling and Langebaan Road were used for the calculations. The average recharge was estimated at 0 – 25% for Langebaan Road and 10 – 30% for Darling. Potential evapotranspiration was calculated with the Penman method.

The model domain focused on the area around Langebaan Road, between Hopefield, Langebaan, Velddrif, Berg River and Sout River. The two-dimensional flow model that was proposed by Boonstra and De Ridder (1981) was adapted to be able to handle the three-dimensional flow problem. It is a finite difference model with polygons. Specific storage coefficients are assigned for each internal node, with hydraulic conductivity values given to the boundaries between adjoining nodes. The polygons had irregular shapes. The thickness of the layers was derived from the isopach maps.

The modelled area was the best-known section of investigation area. There were still relatively little data available for use in the model. As a result of the lack of water table data only few suitable monitoring points could be used in the model. The model was done in three layers:

Layer 1: Semi-confined layers A, B and C were grouped together to form one thick semi-confined aquifer with transmissivity values equal to sum of individual transmissivities and thickness sum of individual thicknesses of aquifers and intermediate aquitards.

Layer 2: aquitard c, which was found in entire study area.

Layer 3: unconfined aquifer D.

The internal nodes were limited to 65 because of a lack of suitable boreholes. A further 32 nodes were used to simulate boundaries of the system. The model greatly simplified the true groundwater flow, with the results giving an approximate solution of regional groundwater flow. Introducing abstraction thus only yield an approximate indication of the lowering of the regional water levels. Timmerman (1988) recognized that the model was not suited to study local groundwater problems and that more detailed models would be needed, with a more detailed data network.

The boundary conditions were complex because of the irregular shape of modelled area. No-flow conditions were set at granite outcrops, and between Langebaan Road and Elandsfontein, while head-controlled boundaries were set with the river and sea. The basement boundary was considered impermeable. The top boundary was the water

table with flow across boundary in form of infiltration of precipitation – the calculated recharge.

The model represented the water levels in the lower aquifer layer more accurately, but the central area (where artesian pressure exists) provided a challenge. It is thought that the lack of observation points and spring flow that was not included in the map, could be part of the reason for the discrepancy in the upper aquifer layer. An underestimation of evapotranspiration may have added to the results. The discrepancy in the lower aquifer layer may be the result of the overestimation of leakage from the upper aquifer layer to the lower aquifer layer or because of inaccurate initial piezometric levels.

The scenarios that were used in the model included abstraction, prolonged drought conditions and a combination of the two. When an imaginary yield of $3.15 \times 10^6 \text{m}^3/\text{a}$ was applied in scenario 2 (prolonged drought and abstraction) the cone of depression was too deep, as it is advisable to keep the piezometric level below the top of the semi-confined layer. When the abstraction rate was reduced to $2.8404 \times 10^6 \text{m}^3$ the drawdown at the abstraction point was 20m, which correlates rather well with the actual drawdown after the wellfield became operational (11m) and the drawdown during the recent drought. The model predicted an impact from Saldanha Bay to Berg River with a drawdown 50cm on the outer edges. This raised the possibility of saltwater intrusion. The model shows that the aquifer compensated on the abstraction by a change in storage. The long-term max abstraction rate was recommended at $6.32 \times 10^6 \text{m}^3/\text{a}$, when the possibility of saltwater intrusion was not considered. The limitations of the model included lack of data input, and the fact that the model only produces regional impacts, it could not be used as a management tool.

The results of the model gave a conservative estimate of abstraction potential at $15 \times 10^6 \text{m}^3/\text{a}$. If the findings of the model would be extrapolated over the entire study area a yield of $50 \times 10^6 \text{m}^3$ could be possible.

The Timmerman model gives fairly good results considering the lack of monitoring data and reliable data points. It was also developed for only a part of the Langebaan Road aquifer, and the possible recharge coming from the granite hills were excluded. The no-flow boundary between Langebaan Road and Elandsfontein aquifer units and the impermeable basement may have added to the anomalies that was found in the model.

It differs from the conceptual model provided in Chapter 5 mainly through the no-flow boundaries between the Langebaan Road and Elandsfontein aquifer units, as well as the Elandsfontein and Grootwater aquifer units, and the fact that the clay layers are seen as continuous in at least the Langebaan Road and Elandsfontein aquifer units. Timmerman also considers only local recharge, while the conceptual model considers the possibility that a large percentage of the recharge may come from further afield.

6.2 Berg WAAS (2008)

The model of the Langebaan Road and Elandsfontein aquifer units constructed under the Berg WAAS project was a fully, 3-dimensional finite element model. It comprised

approximately 2000km² and consisted of 7135 prismatic elements (see Figure 145). Topographical divides were seen as boundaries, as well as lines across observed groundwater contours. No-flow boundary conditions were applied to these. The ocean to the southeast and the northwest were seen as constant heads. The model consisted of 5 layers. Data sets that were used included:

- Borehole depths that were sourced from the NGDB (now the NGA), with shale and granite used as an indication of basement rocks;
- Offshore basement data of De la Cruz (1978);
- Spot heights on bedrock outcrops as indicated on 1:250 000 geological maps.

Recharge data comes from a modified version of the Breede River Basin Study (BRBS) method (DWAF, 2003). Recharge over the modeled area was about 1.22Mm³/a. Data from the Water Use Authorisation and Management System (WARMS) provided information on groundwater abstraction, which was 3.6Mm³/a. The assumption was made that the rivers in the area act as a sink to the aquifer units. River stages were placed 1 – 3m lower relative to water level distribution based on initial estimates of the modelled groundwater levels, topography and measured water levels. A complete summary of parameters is given in Table 23.

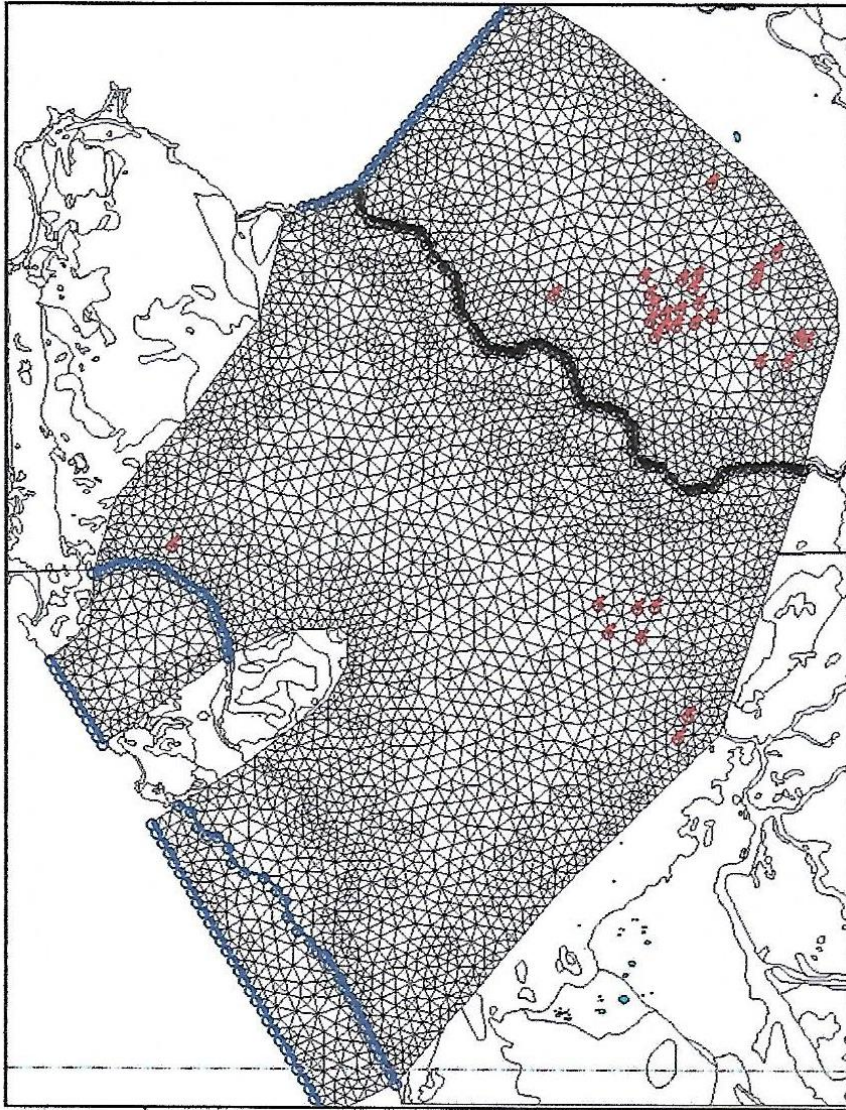


Figure 145: Boundary conditions and the model mesh: The Upper Model Surface. Red nodes indicate abstraction wells, black nodes represent transfer boundaries and blue nodes indicate constant head boundaries (DWAF, 2008).

Table 23: Summary of input parameters (DWAF, 2008).

Model Input Parameter	Source	Type
Topography	100m DEM	Fixed
Bedrock topography	Literature and NGDB (NGA)	Fixed
Layering	Based on geology and numerical requirements	Fixed
Hydraulic conductivity	1 st approx. from typical literature values	Steady-state calibration
Storage	1 st approx. from typical literature values	Transient calibration
Porosity	Typical literature values	Fixed
Recharge	BRBS method (DWAF, 2003) at 100m grid scale	Fixed for steady-state calibration, varied for transient scenario testing

Abstraction	WARMS	Fixed for steady-state calibration, varied in transient scenario testing
River stages	Assumption based on DEM and 1:50 000 topo sheets	Calibration
Transfer rate	Assumption based on data	Calibration

The calibration standard of the model was set within 10% average errors to observed point data. Groundwater fluxes and groundwater levels compared to topography was used as additional guides. The following parameters were used to consider the numerical model calibrated:

- Model basal layer within palaeochannels calibrated with $K_x = K_y$ of approximately 10m/d;
- Discontinuously low K layer overlies the basal layer, at $K_x = K_y$ of 0,01m/d;
- Upper layer with a K of 10m/d in most areas, with some of the areas in the south at about 1m/d;
- The vertical K was taken as an order of magnitude smaller than the horizontal K.

The results of the model showed that the ocean was the most important sink to the aquifer system, and that the Berg River was on average a sink in the steady-state model. The recharge as an inward flux was calculated as 59 800m³/d, with a flux out of the model of 32 800m³/d for the ocean and 27 100m³/d for the rivers. This left the system with an imbalance of 100m³/d, making the flux out of the system larger than the flux into the system. If an abstraction of 10 100m³/d are added to the model, the deficit increases to 1000m³/d. Different scenarios were tested in the transient model. It was found under one scenario that it would be possible to abstract groundwater from the Elandsfontein aquifer unit without affection the water levels at potentially sensitive receptors, such as the Langebaan Lagoon. The scenario testing MAR found that it should be possible to site injection boreholes within the cone of depression created by the wellfield thereby reversing some of the depression.

Several recommendations were made, based on the findings of the model. This included a proper hydrocensus to measure water levels, determine borehole use and recording accurate GPS coordinates. A second recommendation suggested that surface water data availability should be increased and that it should use a universal datum so that it would be possible to compare groundwater levels and surface water stages. The last recommendations suggested smaller scale models for a variety of reasons:

- Increase understanding of the hydraulic nature of the aquirers in connection with differing flow at different depths and surface water-groundwater interaction in the vicinity of the Berg River;
- Wellfield scale for the management of abstraction from storage;
- Optimization of abstraction volume and rate, the position of additional potential wellfields and licencing;
- Optimization of MAR injection volume and rate, as well as borehole position.

The calibration was done with only 21 boreholes for the upper aquifer layer and 11 for the lower aquifer layer. There is data for more than 200 boreholes available, not all of

the same quality. The study area covers a large and complex system, which means that the data points used in the calibration does not adequately represent the groundwater system.

The flux calculations seem to suggest that there must be recharge from somewhere else, since the water levels show a slow and steady decline, that does not fit with the deficit in the water balance. It is thus possible the system does not just receive an inward flux of water from local recharge. The alternative is that the system does not have additional water available for abstraction and that the system will soon run empty.

The model uses a similar area as the one by Timmerman, but a number of differences can be found. One of them is the fact that the palaeochannels continue towards the sea, which agrees with the conceptual model presented above. This model still makes use of the no-flow boundaries proposed by Timmerman, differing from the conceptual model presented in Chapter 5. It is clear that the understanding of the aquifer system has improved, as more data became available, and the similarities between this model and the conceptual model are greater as a result. One of the weaknesses of the model is the fact that a very small number of data points were used to calibrate the model (21 for the upper aquifer layer and 11 for the lower aquifer layer), which tends to oversimplify the system and may cause the resultant product to misrepresent the natural system. There is, however, some justification for this reduction in data points, as there are gaps in the data records and inaccuracies in some of the information available.

6.3 Seyler, et al. (2016)

A numerical finite-element model was developed for three dimensional groundwater flow using the model programme, SPRING. The programme uses finite-element approximations to solve groundwater flow equations. The model domain is represented by a number of nodes and elements with hydraulic properties assigned to the nodes and elements. The model domain for the study was 4 791km² to include all four aquifer units of the Lower Berg River Aquifer System. Originally a three dimensional, four-layered finite-element model was set up, but the upper aquifer layer was later split into two layers for greater stability. The model includes the assumption that the lower aquifer unit and the clay layer pinches out as the basement rises, while the upper aquifer unit pinches out where the bedrock outcrops. The domain was spatially discretized into 96 409 nodes and six node layers, with 5 element layers with 105 394 elements in the form of triangles and quadrangles. The element size varies from 10m in areas expected to have steep groundwater gradients up to 250m in the surrounding areas. A state of dynamic equilibrium was modelled using data from before 1999. Boundary conditions include a recharge, surface water interaction and abstraction. Recharge values of around 5% - 9% (5.5 - 35.5mm/a) over four zones were used. River boundary conditions that depend on gradient were used for rivers. WARMS data before 1999 and the 2002 DWAF hydrocensus information was used to calibrate the model. Fully penetrating wells were given equal heads for all applicable well nodes for the different model or aquifer layers - which is difficult to understand since the boreholes would be screened in a specific layer of importance.

Only 530 of the original more than 1000 data points were used in layer boreholes, and the model was divided into lower aquifer layer, upper aquifer layer and basement layer boreholes. The data was apparently insufficient to distinguish between upper-and-lower surface water flow data could not be used as a secondary calibration target as a result of the lack of rating curve. All water level data was thus grouped together for the calibration.

The initial conditions were interpolated from a full steady-state water level data set using Bayesian interpolation, i.e., co-kriging to establish the correlation between surface topography and the groundwater elevation. Existing hydraulic conductivities estimations were used with the vertical conductivities set at 10% of the horizontal component.

The impact of the different pumping rates gave a fairly stable radius of influence with the magnitude of drawdown increasing with the increase abstraction. It was found that two factors would limit the yield from the aquifer. The first is inducing recharge from the Berg River, which is considered unacceptable because of the higher salinity in its lower reaches. This should not be a problem if it is found that the aquifer matrix can sufficiently purify the water by the time that it reaches the abstraction point. The second condition is maintaining the confined state of the lower aquifer layer. The study suggested that spreading the abstraction of the same volume over six boreholes instead of the current three would enable the abstraction of a higher volume without exceeding the drawdown limit.

Suggested yield volumes are set as larger than $3.5 \times 10^6 \text{m}^3/\text{a}$ to smaller than $5.5 \times 10^6 \text{m}^3/\text{a}$. the study found that even at the current rate of abstraction that recharge or leakage are induced from the upper aquifer layer to the lower aquifer layer and that in compensation the discharge to the surface water bodies and the sea is reduced. This could be seen very clearly in analyzing some of the water level data for the last two years. The model predicted impacts on the discharge to the sea at Saldanha Bay, St Helena Bay and Langebaan Lagoon. The latter confirms the hydraulic link between the lower layers of the Langebaan Road and Elandfontein aquifer units.

This model is the closest to reflecting the observations made in the field and the analysis of the available data. It is thus also close to the conceptual model presented in Chapter 5.

6.4 Summary

Models are only as good as the input and the conceptual understanding of the relevant study area. There would, in the end, never be a totally wrong or a completely correct model. The differentiation would rather be in comparisons – a good model being as close to reality as possible, while a bad model would reflect the bias of the modeler or his client. The type of model will depend on its ultimate purpose. If it is to be used for management decisions, it needs to be done with care, as a model is not a black box that

contains all the answers. Nature is far more complex than the models that can be developed.

The Timmerman (1988) model was successful at the time it was developed as a result of the detailed investigations that was done and that then went into his conceptual model. Some of the assumptions in the conceptual model may have added to the discrepancies in the results of the model, but the advantage of a long data record was not there. It would be worthwhile to use the information from the investigations by Timmerman and combine it with the long monitoring data record and results from recent drilling.

The Berg WAAS model built on the work of Timmerman (1988) and added valuable information which provided us with a better model and understanding of the aquifer system. It had the benefit of a longer data record and more data points than Timmerman had for the construction of his model, as well as the development of the wellfield that could provide information on the response of the aquifer system to abstraction. It did not sufficiently capitalize on this additional information as the model only used a limited number of data points.

The model by Seyler, et al. (2016) could probably do with some improvement, especially since the extension of the Langebaan Road wellfield and the new Hopefield wellfield provided some new information that was not available at the time the model was developed. It is, however, the best that have been done so far, and it could provide a good basis on which to build, especially since it so closely resembles the conceptual model presented in Chapter 5.

Chapter 7: Management Strategies



Sampling at G33317 (22 May 2017)

South Africa is a water scarce country. The industrial development of the country depended on the building of a large number of dams and piping water over long distances. This has made the country largely dependent on surface water. The recent drought, especially in the Western Cape, has demonstrated the lack of diversification of water sources. It has also shown that it is possible to build more resilience into the water supply system when there is diversification in source water and conjunctive use.

Until 1998 groundwater was managed separately from surface water and was seen as a private resource. The National Water Act of 1998 (Act 36 of 1998) (NWA) was forward-thinking in that it saw groundwater as an integrated part of the water resource system and as a common resource to be managed by the minister of the Department of Water and Sanitation (DWS) as custodian of all water resources. Various tools had been provided to manage the water resources equitably, sustainably and efficiently. A limited understanding of groundwater and the prevalence to revert to engineering principles when managing water resources had led to an Act that is mostly written with surface water in mind. The tools and principles that had been tested for surface water were used directly for groundwater without considering the practicalities in applying and enforcing the NWA. This did not seem to provide too many problems, as groundwater was not considered a viable, sustainable water resource, and the use of groundwater was mostly limited to private use for garden irrigation, in agriculture for irrigation and for bulk supply in many small towns where surface water was not available.

This has changed drastically during the recent drought (2016 – 2018) that affected the whole country, but especially the Western Cape. Groundwater was suddenly seen as the

solution to the problem of water availability. Groundwater developments were taking place in areas that were not considered before and there was a need to find methods to manage this valuable resource with sometimes very little data and information to start with. Adaptive management may be one option of how to manage groundwater resources with the complexity and uncertainty that is associated with the resource as it provides the tools for learning from the response to management measures that was put in place and allow for the adjustment of management based on what was learned (Seward, et al., 2006). Monitoring is thus an extremely important part of this process, together with the analysis of the data collected.

This chapter provides the action plan for the establishment of an adaptive management strategy that can be used in coastal aquifers based on the twelve principles of groundwater management. It would be possible to apply the action plan the development of an adaptive management strategy on other groundwater systems, but the site-specific information will differ. The principles will be discussed first. It will then be included in an action plan for the development of the adaptive management strategy.

The action plan contains site-specific information for the Lower Berg River Aquifer System, that can be used as a guideline with timeframes for the development of the adaptive management strategy. It also includes suggested timeframes for the review of the adaptive management strategy. The action plan does not include all the points that may need to be included, since this should ideally be done in consultation with all the relevant stakeholders. They may be aware of additional issues that was not known at the development of the action plan. The local municipalities are very important stakeholders in this process, and they should be included, together with other government departments – both national and provincial -, the landowners, water users and other interested and affected parties.

7.1 Adaptive Management Strategies for Coastal Aquifers

The experience gained in the coastal aquifer units of the Lower Berg River Aquifer System, especially with the Langebaan Road wellfield, its extension and the development of a second wellfield near Hopefield were used in developing the adaptive management strategies for coastal aquifers. There are twelve principles (See Figure 146) that need to be considered in the management of groundwater, as described by Fourie (2019; 2020), which includes an adaptive management plan for aquifers. This description includes a discussion with some important details under each principle. Figure 146 is here shown as a series of squares, but it actually becomes a network of interlinking principles as can be seen from the discussion below.

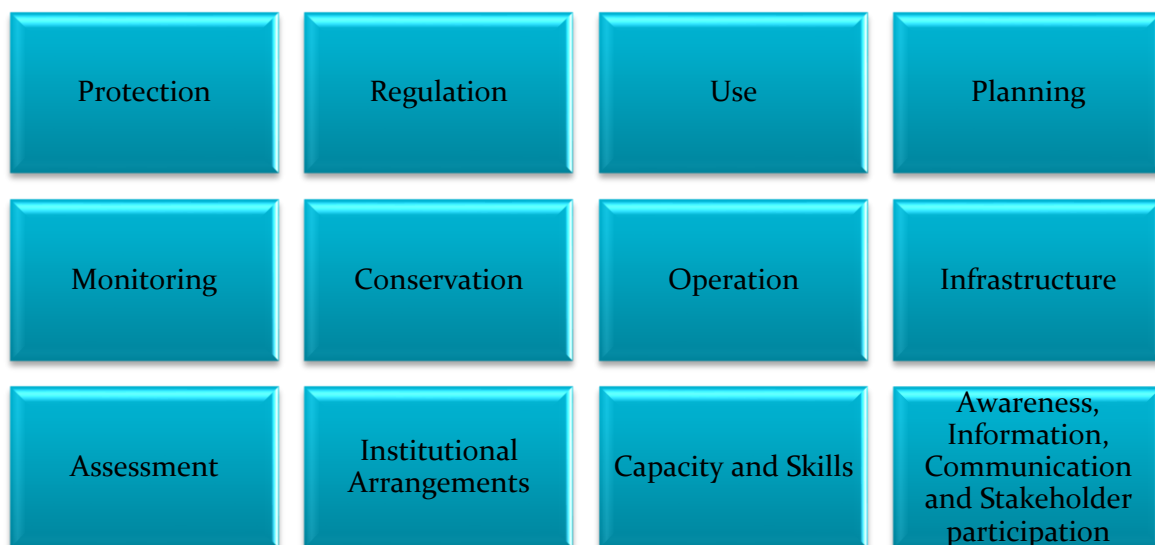


Figure 146: The twelve principles of groundwater management (Fourie, 2019).

Each of these principles should find a place in the development of a groundwater management plan. It is possible that not all principles, or components of the principles, can be included in a local groundwater management plan, as it does not lie within the delegated authority of the local stakeholders. It is, however, important to have collaboration between different tiers of government and stakeholders to ensure the success of the groundwater management plan. The groundwater management plan described by Fourie (2019) provides a good framework on which to build. The discussion that follows, and the action plan provides more detail with which to flesh out the framework provided.

7.1.1 Protection

Protection zones of important groundwater sources should become a matter of urgency, as it is better to prevent pollution and degradation, than to have to remedy it. In Denmark the principle is stated in the words: “Prevention of pollution before cleaning” It should be done at different levels and should be considered in land use planning and special development plans. In some areas, the quality of the groundwater is good enough to supply to the domestic user with minimum treatment. The Cape Flats aquifer is a good example of how poor land use planning and lack of protection zones added to the degradation of an aquifer. Spatial development is done at a Local Municipal level, and land use planners should build groundwater protection zones into their planning. It should be done in consultation with relevant stakeholders.

The Lower Berg River aquifer system was classified as special aquifer, with the Langebaan Road aquifer unit declared a Subterranean Government Water Control area in 1976 and Grootwater aquifer unit following in 1990. Even though it seems that the declaration for Elandsfontein and Adamboerskraal aquifer was never formalized according to available documentation, the intention was there, and it was recognized

as such in the first gazetting of the General Authorisations in 1999 and its revision in 2004 (RSA, 1999; 2004). The importance of the Lower Berg River Aquifer System was thus recognized, and the intention was to protect the system.

The vulnerability of the groundwater systems has been classified as high to extreme (Musekiwa and Majola, 2011, DWA, 2013b). The vulnerability map provides an indication of the tendency or likelihood of contaminants to reach a specific position in the groundwater system after it has been introduced above the uppermost aquifer. It has been ranked as least vulnerable, moderately vulnerable, and most vulnerable. The least vulnerable category is for regions that is only vulnerable to conservative pollutants in the long term when continuously discharged or leached. The moderately vulnerable areas are areas that are vulnerable to some pollutants, but only when continuously discharged or leached. The most vulnerable aquifer regions are those which is vulnerable to many pollutants except those strongly absorbed or readily transformed in many pollution scenarios (DWA, 2013b). Unfortunately, this mapping is at national scale and more detail aquifer level mapping need to be done for practical and useable practices.

The susceptibility of the aquifer system was ranked medium (value of 4) to high (value of 9) (DWA, 2013a). The groundwater susceptibility map indicates the qualitative measure of the relative ease with which a groundwater body can potentially be contaminated through anthropogenic activities and includes both aquifer vulnerability and the relative importance of the aquifer in terms of its classification. The susceptibility matrix is given in Table 24.

Table 24: Susceptibility matrix (DWA, 2013a)

Aquifer Classification				
		Poor	Minor	Major
Vulnerability	Least	Low 1	Low 2	Medium 3
	Moderate	Low 2	Medium 4	High 6
	Most	Medium 3	High 6	High 9

Over-abstraction of the aquifer system may lead to the intrusion of brackish groundwater and surface water from the Berg River and the smaller rivers in the area, as well as saline water from the coast. An additional impact from over-abstraction may be land subsidence, and potentially the collapse of the lower aquifer layer. Irrigation agriculture have the potential of salinisation of the soil and ultimately the groundwater. The potential evaporation for the area is high in summer, increasing the potential for salinisation. It should therefore not be practiced near or on the wellfield. MAR could be used as a strategy to protect the aquifer system against the intrusion of brackish or saline water, and also to stabilize the water table.

The crude oil pipeline runs through the Elandsfontein, Grootwater aquifer units, as well as the Atlantis aquifers. The Strategic Fuel Fund (SFF) crude oil storage tanks are in the

lower part of the Langebaan Road aquifer unit, with additional crude oil storage tanks in construction. The R27 road runs through a part of the Langebaan Road, Elandsfontein, Groundwater and Atlantis aquifers. This is just one of many routes that crisscross these aquifer units. It thus creates the possibility of leakages and spills along these roads, that can pollute the environment and ultimately the groundwater.

The handling of pollution incidents should be clarified. In the Western Cape pollution incidents are handled by both the Provincial Department of Environment and Development Planning (DEA&DP) and DWS when there is a potential impact on water resources. The lines of communication between should be set out clearly, together with the roles and responsibilities of the different units within DWS. When a pollution incident occurs, it is important to react as soon as possible to reduce the impact that the pollution incident may have. Problems with communication, chain of command and authorization to carry out investigations coupled with lack of laboratory facilities created problems and incidents were not investigated. This means that the best possible remediation plan could not be recommended. Plans and procedures should be in place at a local level on how to respond to pollution incidents. This would include reporting to authorities.

A possible suggestion on how to handle pollution incidents, based on experience in the past, is to report it to the relevant officials at DEA&DP as soon as the pollution incident occurs or when a member of the public, industry or the municipality becomes aware of pollution. The official at DEA&DP will then contact the relevant official at DWS. The two officials will then investigate the site together to decide on future action. Testing of both soil and water samples are important, and budget should be allocated for this with both departments. This is a critical step, as the results will help to determine the way forward. If the industry reports the incident at one of their sites, it would be advisable that a representative of the industry and their consultant meet with the officials of DEA&DP and DWS with a proposed remediation plan. In an industrial case, the industry should provide regular feedback to the two departments on pollution levels and remediation success, with DEA&DP being the leading department.

A number of mines are found within the study area. Not all of them have a direct impact on the aquifer system, as it is outside the boundaries of the system, e.g., aggregate or granite mines. Several mines are, however, found inside the boundaries of the aquifer system, and special precautions should be in place to prevent pollution or degradation. The phosphate mine at Elandsfontein has to dewater the mining pit for the safe continuation of operations, and MAR is part of the operation to inject the extracted water to ensure the continued flow of groundwater downgradient from the mine site. MAR is thus used to ensure the protection of sensitive ecosystems at Geelbek on the Langebaan Lagoon and the continued functioning of the aquifer system.

The West Coast Aquifer System is linked to a number of ecologically sensitive sites, such as the Langebaan Lagoon, which is a RAMSAR site. The link between the groundwater

system and these ecosystems needs to be studied further, monitoring should be put in place and measures should be determined to protect these sensitive sites.

A **protection strategy** should form part of a groundwater management plan. It should thus include measures for dealing with over-abstraction, wellfield protection at different levels, land use planning, disaster mitigation dealing especially with pollution incidents, and protection measures around sensitive ecosystems. This principle would be closely linked with the principle of monitoring, as well as regulation.

7.1.2 Regulation

South Africa has some of the best water related legislation in the world, but the challenge lies in the application and enforcement thereof. There is a culture of non-payment and not complying to legislation in the country that makes it difficult to manage water resources optimally. Authorisation of different water uses in the form of water use licences (WULs), general authorisations (GAs), existing lawful use (ELU) and Schedule 1 was an attempt to regulate groundwater use. In addition, tools such as the Reserve, Resource Quality Objectives and Water Resource Classes were meant to provide standards that could assist in regulation. There were, however, certain things that was not taken into consideration when this system was developed (See discussion in Chapter 2 under Questions of Scale and Measurements), and these oversights complicate regulation of groundwater use. An additional complication to regulation is lack of capacity in the Compliance and Enforcement section of DWS and lack of clear roles and responsibilities between different levels of government. The compliance and enforcement section should be strengthened to be able to handle the problems with non-compliance and unauthorized use of water resources from a national level.

It is, however, possible to provide a way of ensuring regulation and monitoring of compliance on a local level. The CMA needs to take up its role in regulating water use, with some of the responsibilities devolving to municipal level and even to the level of the water user's associations, as they are closer to the source and may have more people to assist with the task. There is currently no water user's association for the West Coast Aquifer System, partly because the process of forming new water user's associations has been stopped by DWS. The Langebaan Road Monitoring Forum can be the starting point for the formulation of a more inclusive forum for the Lower Berg River aquifer system, and eventually a WUA with regulatory functions.

The responsibility of regulation should ultimately lie with each water user, who should take responsibility for their own use or potential impact on the resource. The WUL conditions for both the Saldanha Bay Local Municipality and the Elandsfontein mine stipulates the formation of a monitoring committee to oversee the groundwater related activities. This should provide some control over the aquifer system and the regulation of groundwater use.

Regulation should be built into a management plan, in consultation and collaboration with stakeholders. Individual water users can become the biggest asset in groundwater management when they understand that it is a shared resource and takes responsibility

for it. The management plan should include the proper authorization for water use activities. It should also have measures in place to ensure the efficient and sustainable use of groundwater.

7.1.3 Use

Groundwater is a shared resource, with different water users competing for the same resource. This principle is closely linked with the principles of regulation and monitoring. A groundwater management plan should include a way to balance the different competing water uses in such a way that the aquifer system is not detrimentally affected. This includes the sharing of information about the use of the aquifer – abstraction, injection and other activities that may potentially impact the aquifer or lead to its degradation or pollution for the other users of the Lower Berg River aquifer system.

The largest groundwater users in the area currently are the Saldanha Bay Local Municipality with two wellfields, the Elandsfontein phosphate mine and some farmers involved in irrigation agriculture. Most of the farmers and landowners were limited in their use of groundwater as a result of the Subterranean Government Water Control Areas that were declared in 1976 and 1990 respectively. This limited economic and agricultural development for a number of years and helped to protect the resource to a great extent. Groundwater awareness and an understanding of the aquifer system processes, linking it to the principle of awareness, information and stakeholder participation, will assist in ensuring that the use of groundwater will be more sustainable.

7.1.4 Planning

Planning is an important part of groundwater management, and new developments should be identified before it becomes a crisis. Crisis management seldom lead to good decisions. Planning needs to include the principles of conservation, use and protection, as it is important to ensure the sustainability of the groundwater system while protecting the environment against degradations. Planning includes the expansion, renewal and maintenance of existing wellfields, as well as the development of new wellfields. The planning procedures recommended by DWS includes the following steps (Fourie, 2019):

- Conceptual
- Reconciliation
- Prefeasibility study
- Feasibility study
- Option Analysis

It provides the municipality with the best water supply option where feasibility was determined against social considerations, potential environmental impact, economic

and financial viability, technical feasibility, long term land use and regulatory considerations (Riemann, et al., 2010; Fourie, 2019).

One of the biggest gaps in planning has to do with the financial side of it. It is important to include a **costing and evaluation strategy** in the management plan. This should include a **pricing plan**, where the cost to customer should be as close as possible to the cost of supplying the resource. Pricing of water is still very much under the control of DWS and local needs, such as the cost of groundwater development, operations and maintenance needs of wellfields, etc. are often not taken into account. The revenue received from water users should be ringfenced for the maintenance of water infrastructure and future developments. This would enable municipalities to put aside funds for future developments and O&M of existing systems.

The **costing** of groundwater developments should include the actual cost of the drilling, pumping tests and chemical analysis and the capital cost of the infrastructure. Too many groundwater developments fail because costing of drilling and pumping tests in very difficult hydrogeological conditions used the entire budget, with nothing left for the infrastructure development. A high yielding borehole that cannot be connected to the reticulation system has the same value to the water user as a dry borehole. However, the reverse is also true, if the planning and costing only considers the infrastructure side of the project and not the development side. A flexible or phased budget would be ideal, as it will ensure the successful development of the different phases. The budget should include the following:

- Development cost
 - Geohydrological consulting cost (siting, analyzing and recommendation);
 - Drilling cost
 - Pumping tests
 - Chemical analysis
- Capital cost (infrastructure)
 - Pipeline
 - Valves
 - Pumps
 - etc.
- Equipment cost
- Operational cost
- Maintenance cost
- Replacement cost
- Treatment cost
- Opportunity cost
- Environmental externalities
- Economic externalities

The **valuation** of water resources, and groundwater in particular should be reviewed. It is a very important resource that is frequently undervalued, especially compared to

other resources. The value of water should not just be measured at its monetary value, but also its value to the environment. Water resources are often less valued than other mineral resources and runs the risk of being degraded in the process of extracting the minerals.

It would be prudent to conduct a **cost benefit analysis** for each groundwater development. When an aquifer deteriorates as a result of pollution or over-abstraction the net benefit to the community decreases. If this is not corrected the benefit will decrease further till permanent irreversible environmental damage occurs. The cost of a new groundwater development (whether just one borehole or a wellfield) increases the energy costs and the price of water will increase the cost and benefit of the supply, and the volume supplied to the community increased. Pricing can be used to constrain consumption, as the recent drought showed in Cape Town. This, more than the “Day Zero” marketing, led to the reduction in water use. It encourages the efficient use of water and ensures that the utility function of the groundwater user is optimized (Dillon, et al. 2016; Fourie, 2019).

During the recent drought (2015 – 2018), Saldanha Bay Local Municipality received drought assistance from the Provincial Department of Local Government. After consultation with DWS, it was decided to extend the existing wellfield. The infrastructure was, however, insufficient for the distribution of the additional water, which meant that additional infrastructure would be needed. The infrastructure development took place concurrently with the drilling and testing of the boreholes. This meant that the boreholes could be connected to the system as soon as the boreholes were completed. This ensured that the available funds were not spent on the drilling and testing of the boreholes alone, but also the establishment of infrastructure. It is, unfortunately, not always possible to do wellfield development in this manner, as the infrastructure requirements are often dependent on the yield of the aquifer, something that can only be determined once the boreholes have been tested. It does, however, show how important it is to plan the budget in phases for a groundwater development in such a way as to ensure that funds will be available for infrastructure needs as well as the drilling and testing of the boreholes.

The Saldanha Bay Local Municipality has since drilled a second new wellfield that has been connected to the reticulation system. Airborne geophysics was completed recently to have a better delineation of the aquifer system. This information will be used to site potential future wellfields, MAR sites and contribute to the sustainable management of the aquifer system. MAR has been included in the planning done by the municipality, and the capacity has been built into the recent developments. MAR can potentially also be used as a way to potentially treat water of a less than desirable quality, or to polish water that has been treated to some extent, as is the case at Atlantis. This would make it possible to use water of a less than potable standard for MAR to augment the supply.

Planning – which includes land use planning – should be linked to protection, especially since it may impact the status of the groundwater system. This is something Saldanha Bay Local Municipality should look at going forward. It is hoped that the information from the airborne geophysics could add valuable information towards this. It would also

be important to keep climate change predictions in mind during planning, as it necessitates building a water supply system with greater resilience that will make provision for potential future changes.

7.1.5 Monitoring

Monitoring is important in determining the status of the groundwater resource, and it is one of the key elements to adaptive management. The groundwater management plan should thus include an effective **monitoring plan**. The monitoring plan would include the following:

- Quantity – abstraction volumes, water levels
- Quality – samples, field readings, lab analysis
- Distribution of geosites (boreholes, wetlands, pans, river monitoring points, rainfall stations, etc.)
- Periodic pumping tests where necessary
- Electricity consumption
- Equipment condition
- Leak detection

Table 25 provides more details on the different parameters that should be included in a monitoring plan.

Table 25: Parameters that make up a groundwater resource monitoring programme (Fourie, 2019, adapted).

Elements	Parameters	Description
Groundwater	Water levels	Static and pumped levels
	Volumes abstracted (meter readings)	Individual boreholes and wellfield
	Water quality	A sampling plan needs to be setup. The ‘where?’ (location), ‘when?’ (how often) and ‘what?’ (determinants and substances that will be tested) (DWAF, 2004).
Surface water	Water levels	Gauge plate to measure potential impacts of groundwater abstraction on surface water bodies, e.g., wetlands, pans, springs
	Water quality	Indication of groundwater discharge to surface water bodies
Consumption	Volume use from reticulation	Reservoir and district flow meters vs water sales
Rainfall	Volume [mm]	At wellfield and recharge area
	Water quality	Indication of recharge to groundwater system
Equipment / infrastructure	Groundwater resource infrastructure: maintenance	Leakages, breakages, cleaning, spillage (oil, fuel), maintenance or servicing schedule. Monitoring the infrastructure, together with the pump rates and electricity usage can indicate efficiency (DWAF, 2004).
	Pumping schedule	
Environment	Vegetation	Changes in vegetation composition over time

The monitoring plan should not end at the collection of data. It should include a data base for the storage of data, for the analysis and evaluation of the data and finally, the reporting and dissemination of the monitoring data. The data should be presented in such a way that it would add value to the management of the groundwater system and enable better decision-making. All data need to be available to the public to promote transparency and trust (Jørgensen, 2008; Meyer, 2002; DWAF, 2004; NGS, 2017; Fourie, 2019).

This is a very important component of the management strategy, as it may seriously affect the effectiveness of all efforts to manage the aquifer sustainably. It is not possible to manage a resource without monitoring data. The availability of data affects the results of data analysis and as such any management decisions that are made around the management of the resource. Information around other water users, such as the mine on Elandsfontein should be available freely for inclusion in analysis and for decision making, as is stated in the water use licence conditions.

DWS has till recently been the only institution responsible for monitoring in the area, but Saldanha Bay Local Municipality has been doing some monitoring through their consultant. Financial constraints have severely hampered the monitoring done by DWS, which means data gaps, with the resultant effects on the availability of information for decision making. This means that the municipality can no longer depend on the DWS for information, and it will become necessary for them to take on a greater role in this regard.

7.1.6 Conservation

Conservation has to do with the operational rules and should include a **risk assessment**. This will help to determine the use of groundwater at the right time and the real purpose for the use. This is especially important when the municipality have a conjunctive use of different water sources. It would thus dictate the operation of the groundwater scheme and when to rather use other sources, if available (Fourie, 2019). Groundwater is vulnerable to pollution and degradation through over-abstraction, making the need for operational plans and contingencies important. This would include the development of MAR capacity as an adaptive management strategy, even though MAR has far more applications than just the storage of water in an aquifer.

The principles of conservation and use are closely linked and should be linked to incentives to use less water, to make use of less water intensive technology. Saldanha Bay Local Municipality has managed to cut water consumption within its municipality drastically. This should become a way of life to the residents and industry. It is important to keep awareness levels high, and to inform the public regularly about the status of the water supply to the municipality. Providing additional water sources to the system should not negate the drive to save water. Climate change predictions indicate that this area will potentially become drier, with less rainfall and higher temperatures. This should be kept in mind when risk assessments are done and when conservation plans are set up.

7.1.7 Operation

The operation of the groundwater scheme entails the day-to-day management of the wellfield, but it also includes timely maintenance of equipment and infrastructure. An **operation and maintenance plan** would provide a programme for regular maintenance and should include the replacement of aging infrastructure. The principles of operation and infrastructure is closely linked.

Operations includes which pumps will be running for how long, the amount of chlorine to add to the groundwater that is abstracted, which entails regular monitoring of the water quality, changes in water level, as well as other activities that may potentially impact the production of the wellfield. It includes regular monitoring of the condition of the infrastructure for maintenance purposes. This may be done by monitoring electricity use, as an efficiently functioning system will use less electricity than a system that is under strain through clogged boreholes and aging pumps. The Langebaan Road wellfield has not experience biofouling through iron clogging bacteria, like the Atlantis wellfields. It has thus not been necessary to clean the boreholes yet. There is, however, problems with incorrectly constructed boreholes, with sediment flowing into the boreholes. This has thus far only been experienced in monitoring boreholes. Another problem has to do with boreholes that act as a link between the upper and lower aquifer layers, which has potential water quality implications, as does the leaking of water from the confined aquifer layer to the unconfined aquifer layer. An added benefit of regular monitoring and maintenance is that it may reduce the potential for vandalism.

The operations of the two wellfields are done from the Withoogte water treatment plant by the WCDM through a telemetric system. This means that the instrumentation should be calibrated correctly and should be tested for accuracy on a regular basis. This would include verification through field readings.

One of the important factors that should be included in operations is the prevention of water losses from the system, thereby linking it to the principle of conservation. Water is provided to the residents at a cost, and it does not make sense that water is lost in the system – it is not a cost-effective way to run the system. Leak detection systems may help with reducing non-revenue water, both in the bulk system and in the municipal reticulation system, while smart metering could add an additional layer of protection against water losses. Regular (at least monthly) water balances of the bulk, reservoir and distribution networks need to be performed. Bulk flow meters can be installed at strategic locations on the network to perform the water balances between important sections or districts in the network. Smart metering would be the ideal, as it also provides the option of pressure regulation within the bulk system.

7.1.8 Infrastructure

The infrastructure provides the backbone of the water reticulation system and should be maintained regularly. The development of an **infrastructure plan** would be of great advantage, as it would assist in maintaining the reticulation system in the best possible condition. The infrastructure plan should include pipelines, reservoirs, pumping

stations, local treatment of groundwater, abstraction boreholes and pumps, and MAR setup, if used. The bulk pipelines and reservoirs were constructed in the 1940s, as part of the war preparations to provide potable water for the military bases during the Second World War. This infrastructure should be checked regularly and repaired as soon as possible. Replacing aging infrastructure pro-actively may be even better, as it could reduce the down time of the reticulation system. The original wellfield as Langebaan Road was developed in 1998 and 1999. The pumps had been serviced and repaired a number of times, with the largest overhaul of the system after the vandalism of early 2013. The extension of the old wellfield and the development of the new wellfield has added to the infrastructure that needs to be maintained and managed.

7.1.9 Assessment

Regular assessments need to be done on the water use volumes, the abstraction volumes and the status of the groundwater system. The assessment should also include the status of ecologically sensitive ecosystems that are associated with the groundwater system. This would help to determine when it would be necessary for new groundwater developments or the upgrade of the existing wellfield.

A proper assessment of the aquifer system to determine its status and whether it would be able to yield more groundwater was not done before the extension of the existing wellfield or the development of a second wellfield. The situation in Saldanha was very bad during the recent drought, and at one stage the municipality was days away from “Day Zero”. There was, however, a relatively good understanding of the aquifer system and DWS had been doing regular monitoring in the area. The advice given by DWS (Vermaak and Fourie, 2017) for further groundwater development was based on this knowledge and historical exploration work, mainly that of Timmerman (1985a, b, c, 1988). Indications for possible reduction in recharge, could be seen in the data record from around 2010, which means that an assessment of the aquifer system after the most recent developments have become crucial. The WUL conditions have placed the responsibility of this on the Saldanha Bay Local Municipality, but it is possible that they will only focus on the Langebaan Road aquifer unit and possibly the Elandsfontein aquifer unit. The recent airborne geophysics will provide more information for a more accurate assessment. It is not clear whether this now reduces the responsibility of DWS to do its own assessment about the status of the aquifer system as a whole. The principle of assessment here links to the principle of institutional arrangement.

7.1.10 Institutional arrangement

It is important to clarify roles and responsibilities, as it can create a lot of confusion. It can lead to a situation where important things are not done, because it is unclear of who are responsible for it. It would be good to do a structural analysis of everyone involved and how they can contribute to ensuring sustainability and efficiency. This includes the formal and informal structures. It can be done as part of the stakeholder analysis, that will be discussed below.

The West Coast Aquifer System falls within the boundaries of three local municipalities, i.e., Bergrivier, Saldanha Bay, and Swartland Local Municipalities. At this stage, it is only Saldanha Bay Local Municipality that has invested in wellfields in the aquifer system, with the Langebaan Road wellfield, the original Hopefield wellfield that provided water to the town of Hopefield and the new Hopefield wellfield. Saldanha Bay Local Municipality is responsible for meeting the conditions of the WUL and the distribution of the water to the residents within their municipal boundaries. The WCDM is responsible for managing the bulk infrastructure that includes the pipelines and the reservoirs. Neither of these institutions have the ability to act against other water users that may detrimentally affect the groundwater resource that they have an allocation through a WUL. The farmers associations, in the absence of a WUA, do not have any competence to respond to potential unauthorized water uses or activities that may detrimentally harm the aquifer system either. Incidents need to be reported to DWS, who is the only institution to act against unauthorized water use or other potential impacts, as the competence for the management of groundwater resources lies with it. DWS, however, does not have the capacity – limited number of officials and financial constraints – to act timeously against all reported cases of unauthorized water use or potential impacts. This means that it often takes a long time before anything is done about the reported incidents, creating the impression that it is not considered important enough.

One very practical example on the division of responsibility is monitoring. The Saldanha Bay Local Municipality should, as holder of the WUL, be responsible for the most monitoring, as they need to show that they are managing the resource entrusted to them sustainably. This would also be the responsibility of every other authorized water user. The local municipality, as the largest water user, should be able to incorporate the information of all the other water users into their reporting and regional model – if in existence – providing a complete update on the status of the groundwater system. It should also incorporate the monitoring done by the WCDM, as the managers of the bulk system and thus the telemetric systems. The Berg-Olifants Catchment Management Agency (CMA), if it manages to be constituted, would be responsible for monitoring about half of the number of sites monitored by the local municipality and report this information as well as the information from the local municipality to the Regional Office of the DWS. The Regional Office of the DWS will then monitor about a quarter or less of the sites monitored by the local municipality in order to audit the monitoring done by both the local municipality and the CMA. A status report should then be compiled by the Regional Office of the DWS, with recommendations for management decisions, which should then be sent to DWS in Pretoria, where decisions on planning, disaster management, etc. will be made.

The processes described above relating to monitoring are a very theoretical exercise, that has not been implemented. The Berg-Olifants CMA has not been formed, even though it had the status of a proto-CMA at one stage, and it is still a directorate in the Regional Office of the DWS. The delegation of duties has also not been clarified, and

the very poor monitoring that is currently done by the Regional Office of the DWS makes it difficult to determine the status of the aquifer system. Any management decisions made with regards to the aquifer system will thus be based on historic data, creating the possibility of bad decisions that may negatively affect the groundwater systems.

7.1.11 Capacity and Skills

It is important to have people with the right skills and/or qualifications involved in the management of a groundwater scheme. This should be included in the groundwater management plan, and opportunities for training and further education should be included. The **Skills and Capacity Plan** would ensure that officials can manage the groundwater resource and the scheme with understanding and the necessary skills. It is also important to include knowledge transfer and succession planning to ensure that new staff members are trained to replace retiring officials, or to replace people that left. It should not be limited to officials involved in the direct management of the groundwater scheme, but should include officials from the environmental department, finance, supply chain management and human resources. It should also include a programme to equip stakeholders, in order that they may have a basic understanding of groundwater systems, to contribute to decision making and to do their own monitoring as a form of citizen science.

Saldanha Bay Local Municipality have competent technical people, but no one with groundwater expertise. They are using consultants to assist them with their groundwater developments, monitoring and compliance with the WUL conditions. The contract with the consultant is only for a number of years, which will then have to be renewed, or a new consultant appointed. This creates problems with continuity and the new consultant may take some time to get to know the system. This is one of the reasons why the West Coast Monitoring Committee that was formed as part of the licence conditions for the original Langebaan Road wellfield failed. It thus makes sense for each municipality to have their own groundwater specialist on staff to ensure continuity.

Other technical staff is necessary, in addition to a hydrogeologist. This includes pump operators and people who can do the monitoring. It is a great asset to a municipality to have someone who understands the operations, who can do maintenance and understand enough of the system to be aware of when something is not quite right. It is not always necessary for the person to have qualifications to be able to fit this description, but it will be a good investment in the future if the promising staff can be given regular training and the opportunity for capacity building. Saldanha Bay Local Municipality and especially the WCDM has a number of people that understands the system, that has been working at the wellfield and with the bulk infrastructure for some time. It would be important to equip them with the knowledge to ensure the efficiency of the two wellfields.

7.1.12 Awareness, information, stakeholder participation

Awareness about groundwater would increase an understanding for the resource and its importance. It should also include ways to protect it. When you are aware of something you are more likely to take care of it and it may reduce vandalism. Regular sharing of monitoring data may create an interest into groundwater systems.

The groundwater management strategies should also include a **stakeholder plan**.

This plan should consist of the following:

- Identification of relevant stakeholders
- Roles and responsibilities
- Importance
- Interactions
 - Aquifer monitoring forum
 - Ward meetings
 - Newspaper / media

A stakeholder analysis is done to identify the interest of stakeholders in a project as well as their importance and influence over the operation. It can also be used to identify local institutions and processes on which a project may be built and provide a foundation and strategy for participation in the operations of the project. The identification of the relevant stakeholders may show where it may be necessary to create subcommittees to be responsible for specific issues related to the management of the groundwater system. Stakeholders can be defined as “... people, groups, or institutions which are likely to be affected by a proposed intervention (either negatively or positively), or those which can affect the outcome of the intervention.” Rietbergen-McCracken (1998) describes a stakeholder analysis as a four-step process. Step 1 consists of identifying key stakeholders, which includes potential beneficiaries, those who may be negatively impacted, vulnerable groups, possible supporters or opponents and the relationships between the role players. Step 2 is the assessment of the stakeholder interests and potential impacts on the project. This includes the expectations of the stakeholders, the benefits to them, resources that can be mobilized and potential conflicts in reaching the goals set out by the project. In step 3 the influence and importance of stakeholders are determined. This will consist of determining the power and status of each stakeholder, their degree of organization, control of strategic resources, power relationships with other stakeholders and their importance to the success of the project. Step 4 outlines the stakeholder participation strategy, where participation is planned according to interests, importance and influence of stakeholders. Additional effort is required to involve important stakeholders who lack influence in the project and to find appropriate forms of participation. Table 26 contains a partial stakeholder analysis for the Lower Berg River Aquifer System. The classification used was recommended by Rietbergen-McCracken (1998). It includes the local municipalities that is responsible for water service delivery to parts of the WCDM area of responsibility that may potentially benefit from the use of the Lower Berg River Aquifer System. Currently, it is only Saldanha Bay Local Municipality that is actively developing the groundwater potential of the aquifer system. This analysis should be updated and completed in conjunction with the

relevant stakeholders, as they may add additional information and stakeholders that someone from outside the structures may not be aware of. Arcelor Mittal, one of the industries mentioned in the table recently announced their closure. They were one of the important stakeholders in the area.

Table 26: Stakeholder analysis for the Lower Berg River Aquifer System.

Stakeholders	Importance (U = Unknown; 1 = little/no importance; 2 = some importance; 3 = moderate importance; 4 = very important; 5 = critical player)	Influence and power (U = Unknown; 1 = little/no influence; 2 = some influence; 3 = moderate influence; 4 = very influence; 5 = critical player)	Effects of project on interests + / o / -	Interests positive impacts	Concerns negative impacts
	Government institutions				
	National				
DWS	5.	5.	+	Improved management of the resource; more information available to inform management decisions	Unrealistic targets set as a result of limited understanding
DEA	3.	4.	+/-	Improved groundwater management may have positive impact on the environment	Groundwater development may have negative impact on the environment – availability of resource reduced
DMR	2.	2.	o	Additional water in the water supply system that may be available	May lose areas for mining, if areas earmarked for municipal water supply
DAFF	4.	3.	+/-	Improved management of resources, decreased possibility of pollution or degradation of resource	Groundwater development may have negative impact on the environment – availability of resource reduced

DPW	1.	3.	o	Additional water in the water supply system that may be available	May affect the activities that are possible in the area
DoD	4.	1.	o	Additional water in the water supply system that may be available	May affect the activities that are possible in the area
Langebaan Road Airforce Base	4.	1.	o	Additional water in the water supply system that may be available	May affect the activities that are possible in the area; greater vigilance required with regard to pollution prevention
	Provincial				
DEA&DP	3.	3.	+/-	Improved groundwater management may have positive impact on the environment and development; additional water supply in the water supply system for development	Groundwater development may have negative impact on the environment – availability of resource reduced
DLG	3.	4.	+	Improved water supply to users in area of jurisdiction; provided drought relief funding	May affect the activities that are possible in the area
SALGA	2.	2.	+	Improved water supply to users	
DA	3.	3.	+/-	Improved groundwater management may have positive impact on the	Groundwater development may have negative impact on the environment –

				environment; decreased possibility of pollution or degradation of resource	availability of resource reduced
	Local				
WCDM	5.	3.	+	Additional water in the water supply system that may be available; improve management of the resource	Additional responsibility in terms of management, treatment, O&M, WUL requirements; lack of capacity
SBLM	5.	5.	+	Additional water in the water supply system that may be available; improve management of the resource	Additional responsibility in terms of management, treatment, O&M, WUL requirements; lack of capacity
SLM	4.	3.	+	Additional water in the water supply system that may be available; improve management of the resource	Additional responsibility in terms of management, treatment, O&M, WUL requirements; lack of capacity
BRM	4.	3.	+	Additional water in the water supply system that may be available; improve management of the resource	Additional responsibility in terms of management, treatment, O&M, WUL requirements; lack of capacity
	Private Sector				
	Commercial				
Retail	3.	1.	+	Greater assurance of water supply	Higher water tariffs
Real estate	3.	1.	+		
	Industrial				
Arcelor Mittal (Saldanha Steel)	4.	2.	+	Greater assurance of water supply	Higher water tariffs

Tronox (Namakwa Sands)	4.	2.	+		
Fish factories	4.	2.	+		
Mining					
Sand, clay, granite, aggregate, calcrete, phosphate, etc.	2.	2.	-	Greater assurance of water supply	Reduced areas where mining is possible
Tourism					
West Coast National Park	4.	3.	+	Greater assurance of water supply	Higher water tariffs
Hotels	4.	2.	+		
Souvenir	3.	2.	+		
West Coast Fossil Park	4.	3.	+/-		
Fisheries					
Aquaculture	1.	2.	+/-	Improved management of resources, decreased possibility of pollution or degradation of resource	Groundwater development may have negative impact on the environment – availability of resource reduced
Commercial Sport					
Civil Society					
Farmers	4.	2.	-	Improved management of resources	Availability of groundwater resource reduced; impacts on agricultural activities
Residents	4.	2.	+	Greater assurance of water supply	Higher water tariffs
NGOs (West Coast Biosphere; West Coast Environmental Protection Association, etc.)	2.	3.	o	Greater assurance of water supply	Higher water tariffs

West Coast Business Chamber	3.	4.	+	Greater assurance of water supply	Higher water tariffs
Media	2.	3.	o	Articles celebrating successes of project; information on developments, etc.	Articles on failures of process; lack of service delivery, etc.
Research institutions					
Universities	1.	2.	+	More opportunities / reasons for research; possible funding	
CSIR					
WRC					
ARC					

In most instances observed thus far, public participation consisted of the identification of stakeholders, and providing information on the new project or policy to the stakeholders. It has rarely gone to the stage of soliciting inputs or contributions from the stakeholders that may impact the direction of the policy or project. If inputs were received, the inputs seldom changed the project or policy from the original. Emergency measures under Section 30 of NEMA also allows for certain processes, such as public participation, to be dropped in aid of expediency of the intervention required. This was the case with the recent drought in the Western Cape, where additional water resources were required for municipal supply. Public participation has thus not been a priority and it has created mistrust in a number of municipalities, which few have been able to resolve.

The management of a shared resource like groundwater can only be done properly with the cooperation of each individual stakeholder and interested and affected party. Providing the necessary information in a transparent way creates trust and lead to a greater awareness about the status of the resource. As a result of crisis management, the principles of stakeholder engagement, transparency, sharing information and awareness was not quite done as it should have been, and it created some issues with certain stakeholder. It is, however, not too late for Saldanha Bay Local Municipality to provide a platform where information can be shared, and stakeholders may become part of the solution to ensure the sustainable management of a very critical resource for the communities that are benefitting from the groundwater developments and those that will benefit from it in the future.

7.2 Management Strategy Action Plan for the Lower Berg River Aquifer System

The interconnection of the 12 principles for groundwater management makes it impossible to illustrate it in an orderly flow diagramme, as each of the principles may be linked to more than one of the other principles. Figure 147 is an illustration of the network of links between the different principles.

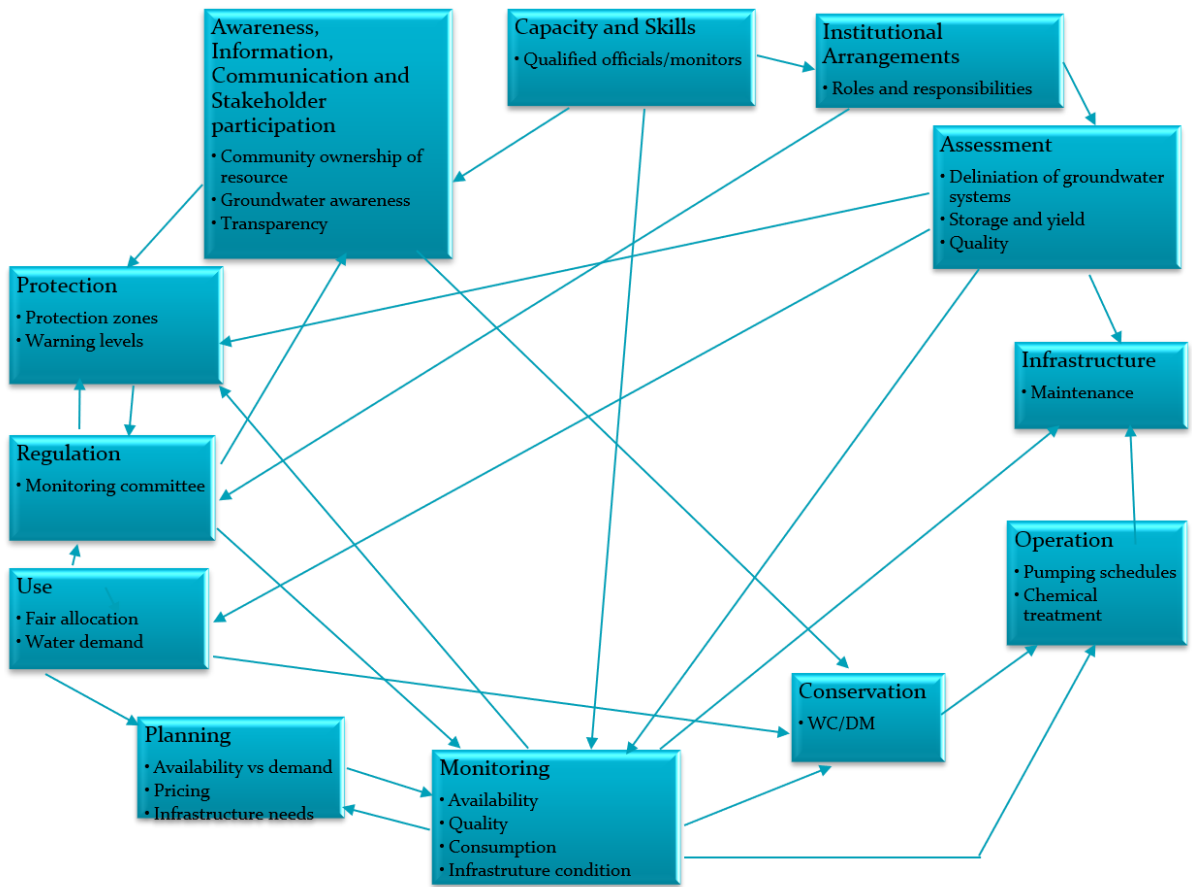


Figure 147: Illustration of the network of links between the 12 management principles.

The action plan in Table 27 provides the items that should be included in the adaptive management strategy for the study area based on the twelve principles discussed above. It shows the cross links between the twelve principles clearly. It is not an exhaustive list of items but contains the most important ones that should be included based on a knowledge of the area. It will be possible that additional points will be added during consultation with the relevant stakeholders. It provides a guideline, and the basis on which to build the adaptive management strategy.

Table 27: Action plan for the development of an adaptive management strategy, using the 12 management principles.

Principle	Action / Activities	Parameters / indicators / guidelines	Principles and policies	Activities to determine success of programme	Timeframe for implementation	Further work needed	Update time frame	Responsible person / institutions
1. Protection	1.1 Delineate protection zones	Wellfield Protection Zone 1: 50m perimeter around each wellfield Wellfield Protection Zone 2: zone of influence of wellfield Recharge area Catchment area Review land use activities in line with protection zones	International best practice Precautionary principle	Monitoring of both water levels and water quality	1 year	Review land use activities in line with protection zones	5 years	DWS, CMA, WCDM, SBLM, relevant stakeholders (landowners, water users, etc.)
	1.2 Set warning levels	Set to ensure that wetlands / springs do not dry up Protection of water levels in private dugwells / boreholes Quality degradation, especially saline / brackish water intrusion	WRCs and RQOs International best practice	Water quality monitoring, especially EC as first indication for saline / brackish water intrusion and quality degradation Water level monitoring	1 year	Thresholds need to be developed, based on monitoring information and in consultation with landowners and other I&APs	5 years	DWS, CMA, WCDM, SBLM, relevant stakeholders

		Protection against over-abstraction and potential land subsidence		in production boreholes, private boreholes and dedicated monitoring boreholes Monitoring of wetlands, springs, pans and associated ecosystem for status		Evaluation of monitoring data to determine possible occurrence of saline intrusion, declining water quality; determining level of risk – improve monitoring programme		
1.3 Re-evaluate and refine aquifer classification	Vulnerability Susceptibility Aquifer status Risk assessment	Gazette on subterranean government water control areas (under Water Act of 1956) International best practice	Monitoring of water levels, quality and environmental parameters	2 years	Re-evaluation may be necessary based on latest information	10 years	DWS, in collaboration with CMA, WCDM, SBLM and relevant stakeholders	
1.4 Develop a pollution handling protocol, with contingency plans and	Precautionary measures Contingency plans Reporting structures	International best practice Precautionary principle	Monitoring programme that includes groundwater quality,	1 year	Register for sources of contamination and level of risk to be set up	5 years	DWS, DEA&DP, CMA, WCDM, SBLM and I&APs	

	precautionary measures	Remediation plans		Infrastructure (oil pipeline), etc.				
2. Regulation	2.1 Ensure transparent allocation of water uses and prioritization of water uses		NWA WRCs and RQOs		ASAP			DWS, with relevant stakeholders
	2.2 Ensure that water users have the necessary authorization		NWA		ASAP			DWS with relevant stakeholders
	2.3 Provide a platform for borehole registration with relevant information collected	Data base for registering boreholes		User-friendly, functional system	1 year		5 years	SBLM, in collaboration with CMA and DWS
	2.4 Develop the necessary legal framework for groundwater management in municipal area	By-laws Standards Guidelines	NWA WSA	By-laws, standards, etc.	1 year		5 years	SBLM, with WCDM, CMA and DWS
	2.5 Develop protocol for compliance monitoring	Protocol for compliance monitoring	NWA	Protocol and cooperation between LM, DM, CMA and DWS	1 year		5 years	DWS, CMA, WCDM, SBLM, relevant

				Monitoring committee				stakeholders
3. Use	3.1 Conduct a socio-economic evaluation of water use	Cost benefit of groundwater as part of conjunctive use			2 years			SBLM and WCDM, with relevant stakeholders
	3.2 Keep a registry of groundwater use	Compulsory metering User profile and use inventory Water demand/supply balance		WARMS data base Metering data base	1 year		5 years	DWS, with relevant stakeholders
4. Planning	4.1 Do proper financial planning	Improved costing and evaluation Pricing structure relevant Cost benefit analysis			Continuously	Status has to be reviewed regularly and the necessary adjustments made	Regularly	SBLM, with WCDM and relevant stakeholders
	4.2 Conduct long-term planning	Alternative sources Mitigation of impacts of climate change Water budget and conjunctive use Future water demands Development scenarios			2 years	Status has to be reviewed regularly and the necessary adjustments made	5 years	SBLM

		MAR/enhancement of supply						
5. Monitoring	5.1 Review and improve groundwater monitoring plan <ul style="list-style-type: none"> • Use existing monitoring programme for interim • Evaluate monitoring plan • Develop more effective monitoring plan • Divide monitoring responsibilities between stakeholders • Develop data sharing platform 	Effective monitoring programme that collects relevant data	WRCs and RQOs	Regular monitoring with analysis of the data to inform management decisions.	Immediately	Optimise groundwater monitoring programme.	5 years	DWS, SBLM, SLM, agriculture, mining, other relevant stakeholders
	5.2 Develop a surface water monitoring plan	Effective monitoring programme that collects relevant data	WRCs and RQOs	Regular monitoring with analysis of the data to inform management decisions.	1 year	Need to develop a monitoring programme for surface water bodies	5 years	SBLM, WCDM, CMA, DWS and relevant stakeholders

						- farm dams, rivers, etc.		
	5.3 Develop an environmental monitoring plan • Develop monitoring plan for wetlands, springs, groundwater dependent ecosystems, groundwater-surface water interaction	Effective monitoring programme that collects relevant data	WRCs and RQOs	Regular monitoring with analysis of the data to inform management decisions.	1 year	Need to develop monitoring for wetlands, springs, pans and other groundwater dependent ecosystems.	5 years	SBLM, WCDM, CMA, DWS and relevant stakeholders
	5.4 Develop a climate monitoring programme	Effective monitoring programme that collects relevant data	WRCs and RQOs	Regular monitoring with analysis of the data to inform management decisions.	1 year		5 years	SBLM, WCDM, CMA, DWS and relevant stakeholders in conjunction with South African Weather Services
	5.5 Develop an operational monitoring programme	Infrastructure monitoring, i.e. leaks and condition of infrastructure		Regular monitoring with analysis of the data to inform	1 year		5 years	SBLM, WCDM, with DWS and CMA

		Consumption monitoring Electricity use		management decisions.				
	5.6 Develop a protocol for the handling and sharing of data	Relevant data basis Management and analysis of data Responsibility and roles between stakeholders Monitoring committee Communication protocol		Regular analysis of data and reporting on findings Regular meetings of monitoring committee with minutes recorded Roles and responsibilities clarified	1 year		5 years	SBLM, WCDM, CMA, DWS and other relevant stakeholders
6. Conservation	6.1 Promote water saving through WC/WDM programme and pricing structure	Effective WC/WDM programme Pricing structure that encourages water saving						SBLM, WCDM
	6.2 Encourage efficient use of water	Incentives for industries, businesses and homeowners for efficient use of water		Water savings devices More water efficient processes	1 year		5 years	SBLM, WCDM
	6.3 Develop conjunctive use programme	Conjunctive use programme MAR		Decision tool for the use of water from different	2 years		5 years	SBLM, WCDM, with CMA and DWS

	and augmentation options			sources at optimal times				
7. Operation	7.1 Develop pumping rules for wellfields	Optimal pumping routine for each wellfield according to capacity of boreholes			1 year		5 years	SBLM, WCDM
	7.2 Develop operational rules for water supply between sources	Optimal operation of bulk supply system			1 year		5 years	SBLM, WCDM
8. Infrastructure	8.1 Develop a maintenance plan	Regular maintenance of infrastructure to limit down time on bulk system Regular survey of subsurface infrastructure			1 year		5 years	SBLM, WCDM
	8.2 Develop a programme for improvement, expansion, renewal and modernization of infrastructure	Latest technology Infrastructure renewal, expansion possible Financial planning			1 year		5 years	SBLM, WCDM
9. Assessment	9.1 Delineate and	Resource renewability/ recharge		Better understanding of aquifer	1 year, continuous		5 years	SBLM, WCDM, CMA, DWS,

	characterize aquifer	Surface water interactions Resource status / hydrogeological characteristics Ecosystem needs / status Land use incentives Vulnerability and risk of aquifer drought Size of aquifer system – storage reserve Resource and quality trends		and associated ecosystems; more optimal management possible				relevant stakeholders
	9.2 Update model of groundwater system	Up to date model with most recent information			1 year		As necessary, at least 5 years	SBLM, WCDM, with CMA and DWS
10. Institutional arrangement	10.1 Define roles and responsibilities	Clear allocation of tasks and responsibilities Different levels of monitoring Financial management (pricing; cost recovery, etc.) Accountability to other stakeholders			ASAP		5 years	SBLM, WCDM, CMA, DWS, relevant stakeholders

	10.2 Develop a conjunctive resource management committee	Monitoring committee or resource management committee to assist with review and decision making Stakeholder institutions and involvement			ASAP		5 years	SBLM, WCDM, CMA, DWS, relevant stakeholders
11. Capacity and skills	11.1 Ensure necessary technical capacity and skills	Training opportunities Recruiting of hydrogeologist and groundwater technicians (appoint consultants as alternative)			ASAP		5 years	SBLM
	11.2 Develop succession planning model	Transfer of knowledge and skills to ensure continued efficient performance of system			ASAP		5 years	SBLM
12. Awareness, information, communication, and stakeholder participation	12.1 Develop groundwater awareness plan	Informed water users, with understanding of groundwater Public awareness Educational programmes		Educational material Newsletters and other material Workshops	ASAP		5 years	SBLM, WCDM, CMA, DWS, relevant stakeholders

		Communication of resource status						
	12.2 Develop a stakeholder engagement plan	Stakeholder analysis Participation of relevant stakeholders Stakeholder ownership Monitoring / management committee		Adoption plan Consultation / information shared with stakeholders Political dialogue on land use Community / stakeholder participation and cooperation	ASAP		5 years	SBLM WCDM, CMA, DWS

7.3 Flow process

The action plan above lists the individual actions that need to be done to ensure the sustainability of the groundwater management in the Lower Berg River Aquifer System. The structure and manner in which the actions will flow will differ. Certain actions will be done consecutively while other processes will be carried out in parallel. Figure 148 provides a flow diagram of how it would be possible to structure an adaptive management plan. It is based on the cycle used in the development of a groundwater scheme. This **Development Cycle** would be the first cycle in the flow diagramme. It would go through the normal processes of pre-feasibility studies, feasibility studies, options analysis, design and implementation of the scheme, reporting / evaluation the scheme, evaluate / review the reconciliation study and the reconciliation study. This cycle will most probably not be done quite as often as the other two cycles in the flow diagramme, but it needs to be done periodically.

The **Operational Cycle** will begin at operation and maintenance of the Development Cycle, as this is the day-to-day functions of managing the groundwater scheme. The next step will be the **Management**. There would be a basic management plan that was developed based on the information from the pre-feasibility and feasibility studies, from the design and implementation of the scheme. The management will include protection zoning, pricing strategy, adaptive management strategies and other management plans.

Monitoring would be needed to ensure that the management plan is obtaining the desired results. A proper **monitoring** protocol would be needed to ensure that the relevant parameters is measured. It should contain the normal monitoring such as electricity consumption, monitoring of the infrastructure, flow measurements, water quality measurement, and water levels to ensure that the abstraction and delivery of water runs smoothly. It should also include measurements that other water users are not detrimentally affected, that there are no adverse effects on the environment. Even though it may not be possible to provide exact levels and volume against which to manage the groundwater system, there could be certain impacts that can be used as warning signs. This includes lowering the water level in an adjacent wetland to more than 1m of its normal average or causing the water level in a private borehole to drop below a certain level. This would, however, mean that measurements would be needed against which to measure the impact of the activities of the groundwater scheme – something that will not be available in most cases when the project starts. Measuring the pressure in the pipelines could act as a warning of leaks. Smart metering can also be used in leak detection.

Collecting all the data would not mean very much without careful analysis and reporting on the findings. The next step is thus **Data analysis and reporting**. Making the data available to the public would add to transparency and build trust. This first group that will evaluate this data and the reports should be the monitoring committee that is made up of representatives of the different stakeholder groups. This information will then be used in the **Evaluation of Management**. The results of the evaluation could be that the management plan needs to be revised, that only parts of it need adjustment, or that

it provides the desired outcomes. A report should be compiled of the findings of the evaluation which would then affect operations and maintenance, with the revisions built into the management plan. If the findings could include the fact that the groundwater scheme is no longer sufficient in supplying the demand, which would lead to the evaluation or review of the reconciliation study. This would then form part of the third cycle, the **Evaluation Cycle**. If the review of the reconciliation study finds that it would not be in the best interest of the municipality to develop a new water source, whether groundwater scheme or other sources, the evaluation cycle would refer its recommendations back to the monitoring or management committee to re-evaluate and change the management plan. If, however, the finding is that additional water should be sourced, a new reconciliation study should be done, which in effect restarts the Development Cycle.

It would be possible to build all the principles of groundwater management into the different components of the flow diagramme and should make it possible to build contingency plans into it that could protect the water supply against climate change and other impacts. This would enable the municipality and their stakeholders to management the groundwater resource in a sustainable and efficient manner.

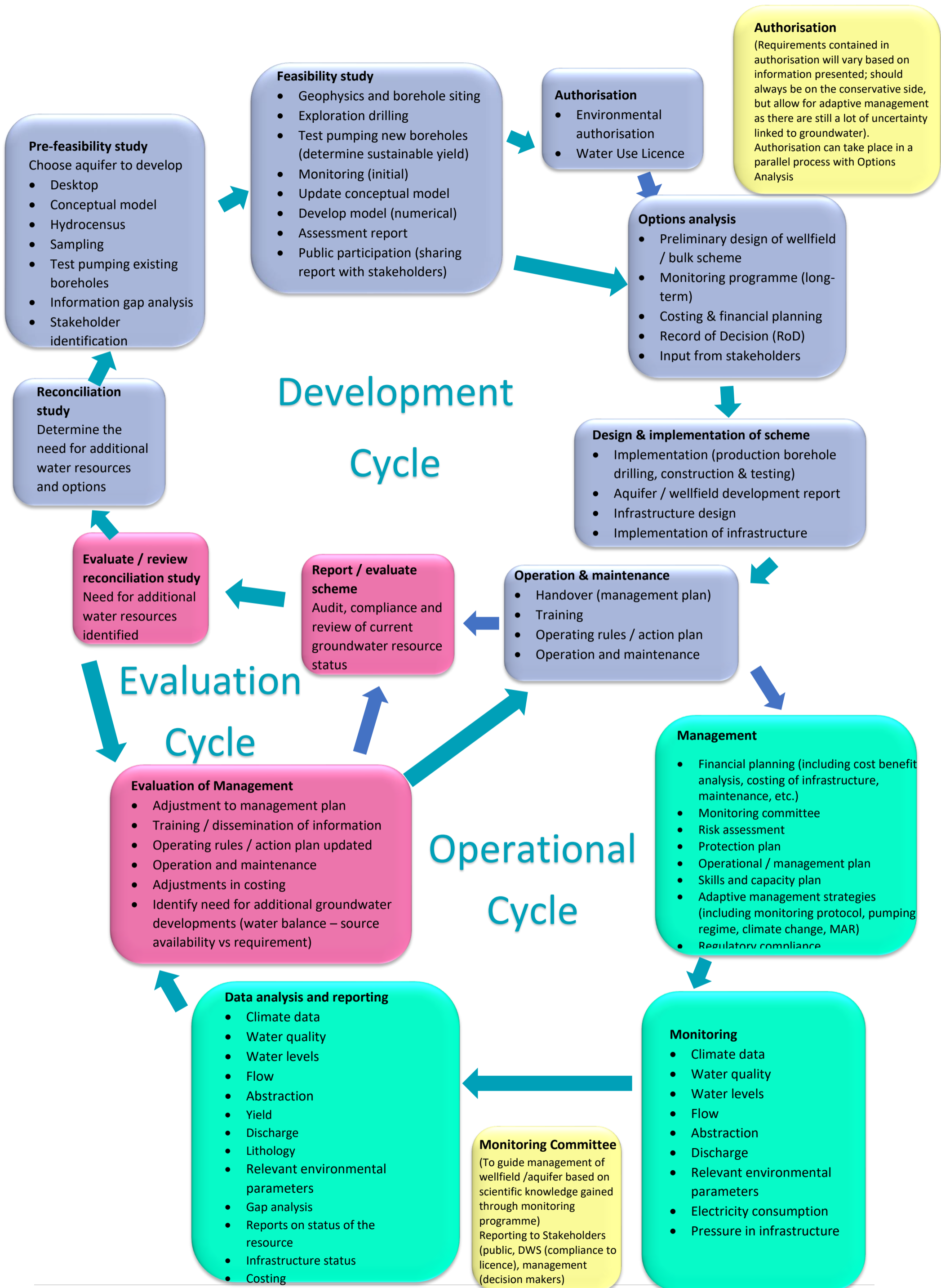


Figure 148: Flow diagram showing the different cycles for the adaptive management of groundwater developments.

7.4 Summary

The legal framework provides the tools that can be used in the management of the Lower Berg River Aquifer System, even though may not be applicable to the unique characteristics of groundwater systems. Groundwater systems are natural systems, where it is impossible to know everything needed to manage it like a dam. In a dam you can measure the exact inflow, the volume in the dam and you can control the outflow. The volume of rainfall, evapotranspiration and the volume that seeps into the soil is the only parameters that engineers do not really have control over. There are a lot of uncertainties and unknowns with groundwater, and it would be impossible to develop management strategies that would be set in stone, or a one-size-fits-all solution. Managing a groundwater system is a learning experience, and just when you think you understand it all, it throws you a curve ball.

Adaptive management can be used to manage a groundwater system with all its uncertainties. It can work within the legal framework of South Africa, and most other countries as well. Competent people should be part of the process, people who understand the aquifer system. It would need the buy-in of as many stakeholders as possible. Not all of them will be happy with all the decisions taken, but they need to be part of the process. Sometimes it is in the voice of dissent that acts as alarm of potential disaster or a solution to a situation. Monitoring would be an important part of the process, as it would provide the information on which to measure the success or failure of the management plan.

8. Discussion



Taking a water level reading at G33333 (22 May 2017)

Groundwater is an inexact science, as with many other natural sciences. There is a high level of uncertainty in groundwater that makes the management of the resource complex and highly frustrating to engineers, who want exact numbers. One of the main problems is that many of the volumes used in geohydrology are estimates that are based on a few measured parameters, such as water levels, water quality, rainfall, temperature, wind, humidity, evaporation, yield determined with pumping tests for example, and the volume that is abstracted. There are other parameters that can be determined with some level of certainty, but most are estimates and cannot be measured. This includes the recharge volume, discharge volume, baseflow volume, flow, storage volume, available abstraction volume and sustainable yield. The groundwater system is also very heterogeneous and may have different characteristics over a short distance – even in a porous aquifer. This all adds up to the uncertainty surrounding groundwater systems and complicates its management.

This inability to link exact numbers to groundwater makes it difficult to allocate the groundwater resource to different competing water users. How do you allocate a water resource to different, competing water users if you do not know the volume that is available? This uncertainty highlights the importance of monitoring the resource, using the right parameters, to give an indication of the sustainability in the use of the resource and to act as warning signs when the resource becomes stressed. Long term, continuous monitoring is necessary, and it should be evaluated regularly.

At the beginning of the research project, it was thought that at the end it would be possible to give a very exact explanation of the Lower Berg River Aquifer System with

the links between the aquifer units all mapped and the flow between them quantified. It would then be possible to give a management plan set in stone that could be followed well into the future. The reality and the complexity of the task hit midway through the WRC K5/2744 project. The aim of the thesis was to develop a management strategy for the Lower Berg River Aquifer System that is based on the current understanding of the geohydrology of the area, using international best practice and the legislative framework that is available. The preceding chapters provide the best information on our current understanding of the geohydrology of the area, which is not much. A large amount of data is available, but the reliability thereof not always certain. The action plan that is provided may address some of the knowledge gaps, but it is very possible that other questions will arise as soon as the current unknowns are addressed.

Coastal aquifers are water bearing geological formations that is hydraulically linked to the sea (Johannes, 1980). Coastal aquifers are found around the world, and their importance should not be measured in size or monetary value alone. They are locally important as water resources, but they perform valuable ecosystem services to the terrestrial and marine environment (Campbell, et al., 1992). The Lower Berg River Aquifer System is one of the largest coastal aquifer systems in South Africa, when looking at its size, but it is a water resource for the West Coast District Municipality to use in conjunction with the surface water of the Berg River and augmented by managed aquifer recharge (DWS, 2015). The management and protection of coastal aquifers benefits the water users and the associated terrestrial and marine environments. Legislation and other management tools have been provided to use in the management of coastal aquifers. Internationally this includes the Water Framework Directive (European Parliament, 2000) and its associated legislation in Europe, the OECD principles OECD (2015) and the Barcelona Convention UNEP-MAP, UNESCO-IHP (2015). The Water Act of 1956 (Act 54 of 1956) only had one tool for the protection of groundwater – Subterranean Government Water Control Areas – which was used for some of the coastal aquifers on the west coast of South Africa (RSA, 1956).

The first objective in order to achieve the aim was to develop a data-supported conceptual model that describes the groundwater process for a coastal aquifer in a semi-arid environment. Chapter 3 contains all the available information in reports and publications of the study site that could be added during this investigation. The first major work was done by Timmerman, Timmerman (K.M.G.) and Vandoolaege (Timmerman, 1985a; Timmerman 1985b; Timmerman, 1985c; K.M.G. Timmerman, 1985; Timmerman, et al., 1985; Timmerman, 1988). Their work was based on the geophysical and exploration of others – one of the most notable being Smith (1982), who provided the basement contours used in the model developed by Timmerman (1988). Their exploration work was very detailed, and it provide valuable detail on the sedimentary layers of the aquifer system (Timmerman, 1988). Other work built on the foundation provided by Timmerman (1988). It soon became clear after the development of the wellfield (Woodford and Fortuin, 2003), and the test MAR in 2008 and 2009 (Tredoux, et al., 2007; Tredoux and Engelbrecht, 2009) that there are gaps in the understanding of

the geohydrology of the aquifer system. Isotope studies such as the one by Tredoux and Talma (2009) raised more questions. During this time, the link between the groundwater and the vegetation, especially groundwater dependent ecosystems in the study area, did not receive much attention and it is therefore not well documented. The surface water groundwater interaction is acknowledged, but the exact interaction never quantified and investigated. The indications of the hydraulic flow between the Adamboerskraal and Langebaan Road aquifer units and between the Langebaan Road and Elandsfontein aquifer units are unmistakable, but further work may be needed. The extent of the clay and calcrete layers and their role in the functioning of the aquifer is still disputed in one form or another.

The second part of objective one was analyzing the data that has been collected, mostly by DWS during their monitoring of the area, with various statistical methods and presented in Chapter 4 – a representative sample thereof, with the rest in the appendices. It is a large amount of data from a 1000 data points or more, with data records in some cases from 1974. It is a deep mine, which probably still hold a number of huge and valuable gems.

Numerous graphs were plotted. Rainfall data from the South African Weather Services, DWS and private landowners were analyzed. The cumulative deviation from mean (Yesertener, 2008) was applied to rainfall with a resultant pattern of 7- to 10-year cycles developing – 3 to 5 dry years and 5 to 7 years in the wet cycle.

Time series graphs of the water level measurements were plotted. These graphs were the first indication of the link between the lower layers of the Langebaan Road and Elandsfontein aquifer units, with G33317 showing a drop in water levels that seems to be linked to the abstraction at the Langebaan Road wellfield. This link was also observed by Woodford and Fortuin (2003) with the impact that the abstraction had on the piezometric levels of G33320. G33246, a borehole in the Adamboerskraal aquifer unit shows similar patterns as some of the upper aquifer layer boreholes in the Langebaan Road aquifer unit, providing an indication of a link between these units.

Water quality data for more than 40 boreholes were analysed. Piper diagrammes and Stiff plots were then generated with WISH (Lukas, 2012). The majority of the boreholes had a Na-CL type water, while calcium and bicarbonate were usually in high concentrations where calcrete were present. Some of the data was used in a PreeqC analysis, and the findings correlated with the Stiff plots. It was interesting to note that the shapes of the Stiff plot for G46105, which is in the basement layer, was similar to that of the Elandsfontein aquifer unit. These boreholes have similar water level patterns as the boreholes in the lower aquifer layer of the Langebaan Road aquifer. This could be an indication that the lower aquifer layer of the Elandsfontein aquifer unit is hydraulically linked to the lower aquifer layer of the Langebaan Road aquifer unit through the basement, or more correctly the shale-granite contact (Woodford and Fortuin, 2003).

The data presented in chapter 4 was then used to develop the conceptual model, presented in chapter 5. Some parts of the conceptual model can be clearly seen from the information provided, and thus backed by facts. Others, even though it sounds logical, are still very much in the realm of philosophy and will need further exploration to bring it into the scientific realm.

The conceptual model developed during the course of this work differs from Timmerman (1988) in that the basement is not impermeable with a thick clay layer from weathered basement material, as there is direct response between the lower aquifer layer and the basement layer – G46105 being one example. There is also a hydraulic connection between the Langebaan Road and Elandsfontein aquifer units, either through the shale-granite contact (Woodford and Fortuin, 2003) or a discontinuity in the basement high (Roberts and Siegfried, 2014; Seyler, et al., 2016). This has been confirmed with both water levels and Stiff plots showing dominant water types. There is a definite hydraulic link between the Langebaan Road aquifer unit and the Adamboerskraal aquifer unit, according to the water levels. This confirms the findings of K.M.G. Timmerman (1985) about the palaeochannel beneath the Berg River linking the two aquifer units. This was further confirmed by Roberts and Siegfried (2014) and Cole (2012) from the work that was done by the Council of Geosciences. The granite outcrops are a potential source of recharge through mountain block recharge and should rather be designated as a constant head where recharge takes place, than a no-flow boundary, as in the model by Timmerman (1988). The palaeochannels do extend to the sea at Saldanha Bay and Langebaan Lagoon (DWAF, 2008; Seyler, et al., 2016). The Cenozoic deposits is not continuous layers of even thickness throughout the study area. This is especially true of the clay layer. Timmerman (1988) acknowledges the fact that the clay layer may be absent at times, especially at the mouth of the palaeo-Berg River, where it was eroded. It also thins out at the edges and are absent at times (See Figure 63). G33316 is at the lower edge of the Elandsfontein aquifer unit, with three piezometers. Two of the piezometers are into the lower aquifer. There was no clay identified in the lithostratigraphy of the borehole, yet it was into the Elandsfontyn gravels. Timmerman (1988) talks about “holes” in the clay layer in the area north of the current wellfield. This was also confirmed by the work of Stettler, et al. (2001). The Elandsfontyn sediments were most probably deposited according to normal river sedimentology, and it would be possible to have consecutive layers of Elandsfontyn gravel in direct hydraulic connection without any clay. This was also noted by Timmerman (1988). The importance of the calcrete layers in the functioning of the aquifer system is not clear, but it is possible that it could act as an aquitard, that stores the water and then slowly releases it to the underlying layers. This possibility was mentioned by Timmerman (1988). It could also function as a protection barrier to prevent the upper aquifer layer from being contaminated by the salt spray, thereby preserving the water quality. This is a distinct possibility, as some upper aquifer layer borehole has the similar water quality as the lower aquifer boreholes (G33505 and G33505B; also, G46023 and G46024).

The option of recharge from the high mountains, as found in the Sandveld area around Lamberts Bay (Nel, 2004), was discounted as a viable option as a result of the thick clay formed by weathered bedrock. Recent drilling along the Colenso Fault System (SRK Consulting, 1996; 1998; 2018; Peek, 2019; Vermaak, et al., 2019a) has indicated that it may be reasonable to consider secondary recharge through the fault system. Local recharge most probably comes from the Darling hills just south of the Elandsfontein aquifer unit and the Malmesbury shale outcrop at Hopefield (Timmerman, 1988; Tredoux and Engelbrecht, 2009; Andries, 2019).

The second objective was to establish an appropriate model for coastal aquifers in a semi-arid environment of Southern Africa by evaluation of existing groundwater models (presented in Chapter 6). The establishment of a model was not within the scope of abilities currently available, so the study had to resort to evaluating other models to see how it was done, how it compares with observations and data analysis, and what can be done to improve on it. Determining an appropriate model would firstly depend on establishing the reason for developing the model. A model and conceptual model are only as good as the dedicated input data that is available. As Timmerman (1988) acknowledged, some models provide a regional picture while others provide the necessary information to use in the management of a system. He classified his model in the first group. It would be necessary to develop a proper model, with all the new developments and its potential impacts of the Lower Berg River Aquifer System. The model of Seyler, et al. (2016) may be a good place to start, as it represents the observations and best possible current understanding of the aquifer system.

The third and final objective was to develop adaptive management strategies that can be used for coastal aquifers in the semi-arid areas of Southern Africa (set out in Chapter 7). There was a brief evaluation of international best practice, principles and legislation in comparison to the South African legislative framework and situation (Chapter 2). This was done by comparing the OECD principles (OECD, 2015) with the current situation in South Africa. It shows that there is room for improvement and growth. It also provides the opportunity to learn from other countries to see what works for them. There was a very harsh look at the tools provided by the South African legislative framework for the sustainable, efficient, effective and equitable management of groundwater resources, with the biggest problem being that surface water conditions cannot be applied to groundwater with its unique characteristic. Most of the evaluation was done in Chapter 2 of the NWA (RSA, 1998). The development of adaptive management strategies was done, using the Danish system (Miliøministeriet, Naturstyrelsen, 2012) as an international example since the country is completely dependent on groundwater for their water supply. The Saldanha Bay Water Quality Forum Trust (Van Wyk, 2001) was used as a local example. The adaptation of the management plan that was developed to the site-specific coastal aquifers in the semi-arid areas of Southern Africa will have to be done in conjunction with the relevant stakeholders, with the action plan that provides as a guideline. The buy-in into a project is far more when stakeholders have been involved with it as early as possible. The

general principles were summarised in a flow diagramme, with more detailed plans developed by Fourie (2019). This could form the basis of the initial interaction with the stakeholders, and it would be possible to link some of this work with the existing Saldanha Bay Water Quality Forum Trust.

Adaptive management can use this information and may thus provide a way of managing the resource to balance out the needs of different water users, that includes the environment, even though the system is not fully understood. Where it is necessary to link volumes for allocation from a groundwater system to water users, it is important to be conservative in the estimation, as it is necessary to have a buffer against droughts and the possible effects of climate change.

Other observations that were made during the course of this research showed other gaps in the management of groundwater resources. There is also a need for more accurate groundwater resource assessments to be done together using the information that was collected during the groundwater interventions connected to the drought. This can be used to produce more up to date groundwater maps – an interactive, updatable electronic geology map that would be available for the general public. This will not remove the uncertainty connected with groundwater systems, but it will provide information with a higher level of certainty.

The maps should take rivers, wetlands, springs, seeps, pans and other surface water bodies into consideration, as groundwater contributes to the sustainability of these bodies through baseflow and discharge. It is also important in ensuring sustainability of the groundwater dependent ecosystems that it feeds and the general health of the ecosystem.

9. Conclusion and Recommendations



Hydrocensus along Langebaan Lagoon (16 July 2015)

The idea exists that you can only manage something if you know everything about it. It was because of this notion that it was believed that the Lower Berg River Aquifer System should be fully understood on a scientific level, before a management plan could be created for the study area. Time and experience, as well as interaction with other scientist working in the same area caused the realization that the system is too complex, and it may thus never be fully understood. Does that then mean that it is impossible to set a management plan, if it is dependent on fully understanding the groundwater system?

Groundwater science is inexact, and there will always be new things to learn, but it is necessary to find a way to manage the resource. Adaptive management has the potential of providing the way of doing just that, by changing the management of the system as more information becomes available. It is, however, important to have continuous, long term monitoring in order for the adaptive management to be successful.

It is thus recommended that the monitoring of the Lower Berg Aquifer System be improved and optimized. It should be done regularly without interruptions and should include the relevant parameters. This would include the monitoring of surface water bodies and ecological systems. The data collected should be analysed regularly using statistical analysis to determine patters that can be used in predictions. This may make the management of the system more pro-active. Resource assessment using new technology and improved data sets would be advised. Airborne geophysics is highly recommended as it would remove some of the uncertainties connected to the basement

contours, the extent of the different layers, especially the clay and calcrete layers, and the connectivity between the aquifer units. Cluster analysis of the available hydrochemistry data should provide more information on the recharge area(s) and volumes.

Groundwater mapping – interactive, updateable electronic maps that include surface water bodies and environment – especially where it is linked to groundwater would be the ultimate in advancement for groundwater management. Adaptive management for groundwater resources, should include conjunctive use, better planning and Managed Aquifer Recharge. Using a conservative estimation of volume groundwater available for allocation would provide a buffer that would be needed for periodic droughts and climate change. Recharge estimations updated and improved but should not play such a big role in the determination of groundwater availability, since there are longer, more complex processes involved in recharge than just the direct recharge. The tools for groundwater governance / management in the current legal framework is not really suited to groundwater resources, but it is the best that is available and should be used till better can be provided.

Further work should be done on the hydrogeological characteristics of the fault systems in the Berg River catchment area, and especially on the Colenso Fault System. The link between these systems and the groundwater systems of the surrounding formations. Investigations should include geophysics hydrochemistry, and isotope studies. Additional drilling of boreholes may also be needed, and could provide valuable information.

Groundwater management is something that you learn by doing. Adaptive management provides the framework in which to do it, without giving free reign to everyone who wants to experiment with our valuable groundwater resources. It provides a platform on which to learn more of the intricacies of groundwater systems and how it links to the associated ecosystems.

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West Coast flowers

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